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CLOSING THE LOOP--OR CAN THE SHIP MOTION SIMULATOR SIMULATE SHIP MOTION

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The main purpose of this report is to document in detail the procedure for insuring that the Naval Biodynamics Laboratory's Ship Motion Simulator (SMS) motion outputs match real world, at-sea ship motion data acquired during sea trials or via validated simulation models. Fidelity of motion is essential to the credibility of results of research conducted utilizing the Ship Motion Simulator.

A second purpose is to present a historical overview of SMS development, and to cite significant research results derived from its use.

Finally, a brief description of the upgrades undergone by the SMS when moved to the Naval Biodynamics Laboratory is included. Keywords:

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CLOSING THE LOOP--OR CAN THE SHIP MOTION SIMULATOR SIMULATE SHIP MOTION?

Gilbert C. Willems

CHRONOLOGY

In early 1969, Human Factors Research Inc. (HFR) completed construction of a 3-axis (Heave, Pitch, Roll) motion simulator at their facility in Goleta, California. This device was designed to duplicate the motion of "sea-loiter" aircraft while on the water, at seas of up to Sea State Five (SS5) [1]. The construction and many of the subsequent experiments were funded by the Office of Naval Research (ONR), Washington D.C. The simulator was operated by HFR for ONR from its inception, through 1976.

Until 1975, the overwhelming majority (perhaps all) major experiments utilized single-frequency, sinusoidal motion as the independent variable, primarily in heave. It was these experiments that resulted in the now famous HFR 3-dimensional Motion Sickness Incidence (MSI) model [2,3].

By 1975 there was great interest in the Navy in Surface Effect Ships (SES's). Two 100-ton prototypes test beds (SES 100A and SES 100B) had been completed and were being tested at sea. Results from these tests and from simulations of a not yet built 2000-ton SES indicated markedly different seakeeping characteristics from that of conventional hull ships. This created concern about the habitability of SES-type ships, leading to a test program sponsored by the Navy's Surface Effect Ship Project Office (SESPO) of the Naval Sea Systems Command. In these tests, the SMS was used to simulate the expected motions of a 2000-ton SES. The motion environment of such craft required extensive upgrading of the heave drive [4] system of the SMS in order for it to respond to the greater heave acceleration levels in the 0.5 to 2.0 Hz frequency range.

An extensive series of 48 hour experiments was conducted in the summer and fall of 1975 with substantial participation by the Naval Biodynamics Laboratory (NAVBIODYNLAB). The NAVBIODYNLAB furnished the subjects, medical support personnel, and installed as well as operated a backup data recording system. The latter turned out to be fortuitous, since it was later discovered that the primary data acquisition system had failed to collect any data, but the backup system did. These experiments comprise the only known major attempt to simulate actual "at sea" motion of a ship. In this case, that of a surface effect ship that existed only as a simulation model. Significant results of these experiments are documented in a number of publications [5,6,7].

In early 1976, ONR funded a joint NAVBIODYNLAB/HFR program to study the incidence of motion sickness under conditions other than single-frequency sine waves. Four motion conditions were generated by combining a fundamental sinusoid with its first harmonic in different phase relationships. The results of this experiment indicated that the single frequency MSI model is not a good model for predicting motion sickness in

complex motion conditions, as it consistently underpredicts motion sickness incidence. The number of experiments however was too small to conclusively prove this for all motion conditions. This study nevertheless generated a number of published reports [8,9,10,11]. Plans were made to extend the complex motion database but the program was not completed.

In late 1976, the Office of Naval Research approved transferring the SMS to the NAVBIODYNLAB in New Orleans, La. in order that SES-type experiments could be conducted more efficiently, using the Command's human subject population. By the time the simulator was dismantled and moved, Navy interest in the 2000-ton SES had waned and the expected funding support for re-installation was not available and was not re-established until mid-1979. One benefit of this lull is that there was time to study and attempt to eliminate the known deficiencies of the SMS, as well as enhance its performance. These upgrades to the SMS were described in 1978 [12] and in mid-1979 construction funds finally became available. Bid opening was in October 1979 and the construction phase completed in December 1980.

The word "relocation" is often used to describe the move of the SMS from HFR to the NAVBIODYNLAB but this is a misnomer. The following is a not necessarily all inclusive list of modifications made as part of the "relocation" process:

a) Entire system was moved indoors into a climate controlled environment. At HFR only the control room was indoors.

b) Tower was extended 9 feet and tied to a 18-inch thick solid concrete wall at four elevations. Original tower was of cantilever design, secured at the foundation only.

c) Upper and lower overtravel buffers were replaced by upgraded ones.

d) Tower rails were replaced and realigned.

e) Carriage was strengthened and the cab support structure upgraded.

f) Both cabs were replaced by much upgraded ones.

g) All electrical power as well as control wiring and all hydraulic hoses were replaced.

h) Air conditioning and heating systems were replaced by improved designs.

i) Heave, pitch and roll feedback subsystems were replaced by improved designs. Pitch and roll gimbal bearings were also replaced.

j) Pitch and roll actuators and servovalves were either replaced or refurbished by the manufacturer.

k) Carriage 3-wheel trucks were replaced by high speed 6-wheel trucks.

l) Heave piston diameter was increased from 3.5 inches to 4.5 inches necessitating new larger cylinder, piping, flow control and safety shutoff valves.

m) Entire control console and associated interlock and monitoring subsystems were replaced by new designs.

n) A comprehensive annunciator system was installed.

o) Number of heave pumps was doubled to four.

p) All hydraulic pumps were converted to chilled water cooling.

q) A backup cooling system was installed for use in case of chilled water outage.

r) A jib crane was installed in the SMS area and an A-frame hoist installed in the pumphouse to facilitate maintenance.

s) An emergency subject extrication sys-

tem was installed.

t) All-new signal drive, data collection and recording systems were installed, as well as a new distribution patchbay.

u) All motors and pumps were remotely located in a pumphouse. At HFR they were outside, clustered around the base of the SMS, creating a serious noise artifact.

v) All piping was installed in trenches below floor level.

In-house work to complete the control and monitoring systems continued until August 1981, when failure of a key valve during shakedown experiments, caused considerable damage to the carriage. Severe funding shortages precluded purchasing repair materials until late in 1982 when repairs were finally begun. Immediately after these repairs were completed, the first of three convenings of an independent commitee established to assess the safety of the SMS for use with human subjects (Man-Rating-Commitee) took place, and resulted in an extensive (and expensive) set of recommendations to be implemented before the system could be man-rated. Implementation of these as well as additional ones generated at the second Commitee meeting delayed final man-rating until November 1984, when the SMS was finally approved for human use. From this time until late 1986 when the Ship Motion program was terminated by the elimination of funding support due to economic reasons, extensive experiments were conducted, using only single-frequency sinusoids as drive signals.

The Ship Motion program was reactivated in December 1987 and preliminary work to render the SMS ready for experiments began shortly thereafter; initial efforts consisted primarily of: 1) identifying and installing a meaningful performance test battery; 2) readying the SMS for tests duplicating actual "at sea" motions; 3) installing a PC-based computer network for administration and scoring of the performance tasks; 4) modification of the static cab to more closely duplicate the interior of the SMS.

Thus in May 1989, twenty years after its genesis, the SMS was finally ready for the first series of experiments that duplicated the motion of an actual ship. In this case, a FFG7-class frigate was simulated using drive signals from data recorded by NAVBIODYNLAB personnel during at sea trials in 1986 aboard the USS Rentz, FFG-47.

INTRODUCTION

The first series of SMS experiments since the reactivation of the Ship Motion program will attempt to determine what effect if any, roll stabilization has on the ability of test subjects to perform certain tasks considered to be analogous to shipboard tasks.

Roll stabilization, whether fin or rudder is conceptually simple. Just as a winged aircraft must bank to turn, a conventional hull ship must heel to turn. Therefore if the ship begins to roll in a given direction due to wave action, this can be counteracted to a certain degree if somehow it can be forced onto a turning maneuver that forces a heel in the opposite direction (rudder stabilization). Fin stabilizers generate differential forces port and starboard of the vessel, thus forcing heeling. The problem is that by the time a helmsman senses roll, it is too late to do anything about it, due to the slow response time of the ship. Roll acceleration however, leads displacement by 180 degrees, being its second derivative. Typical roll frequencies are of the order of 0.1 Hz, yielding a period of 10 seconds. Thus 180 degrees represents 5 seconds and if one deploys transducers that sense the ship's roll acceleration, the latter is sensed 5 seconds before any roll displacement takes place. This is ample time for an automated system to initiate a corrective maneuver. Even if roll rate is measured, rather than acceleration (angular rate sensors are more common than angular accelerome-

ters) the lead time is 2.5 seconds. In mathematical terms, the effect of adding roll feedback to the steering system is to increase the damping ratio several-fold. A higher damping ratio increases the rate at which the oscillations of a resonant system decays [13].

From the recorded data, two segments were selected, one in which the stabilizers were not in use and substantial roll existed, the other in which stabilizers were used. The stabilized segment's roll amplitude was approximately 40% to 50% less than the unstabilized one, this being representative of the known effectiveness of roll stabilization techniques. Environmental conditions during data collection, collection parameters and sample plots of the selected run segments are detailed the the Appendix.

The body of this report describes the process of "tuning" the SMS to properly respond to the drive signals, and presents data which document the performance of the SMS in response to these signals.

METHODS

Overview of the Optimization Process: The procedure for optimizing the SMS for a particular input profile consists of the following basic steps:

1. Determine the spectral content of the input signal. This determines the frequency range the SMS must operate in.

2. Match the polarity of recorded data with the SMS drive signals, i.e. if a positive voltage represents upward acceleration of the ship, it must represent the same motion direction in the SMS.

3. Adjust amplitude scale factors so that the physical motion of the SMS is the same as the ship's. This is required because the amplitudes of the signals recorded onboard the ship are a function of sensor sensitivity and data acquisition path gain; scale factors for the SMS are fixed by design.

4. The heave, pitch and roll drive signals must be phase-matched. These signals are recorded onboard ship simultaneously and are thus time coincident. However, the SMS's responses to these inputs are a function of the dynamics of SMS itself, which results in the introduction of time delays of varying magnitudes which must be compensated for to restore time-coincidence.

5. Optimization of the heave feedback system by manipulation of position and pressure feedback gains and/or addition of compensation networks. For this first series of experiments a new pressure feedback system had to be installed because the original one had been discarded due to unreliable performance.

Pressure feedback system: Since the pressure feedback loop is part of the closed-loop control of the heave axis, failure of any element of this loop could cause potentially dangerous runaway conditions, thus requiring a protective interlock scheme to shut down the SMS if needed. The technique used is depicted in Figure 1: Two identical pressure transducers sense heave cylinder pressure and transmit the electrical signals to circuit card SMG 50 located in card rack "C" of the SMS Control Console. Here the signals are conditioned (AD 522's) summed together (IC1A), subtracted (IC1D and IC2A) and finally scaled (IC1B and IC1C). The output of IC1B goes to the cylinder pressure readout of the Control Console and the output of IC1C goes to the heave feedback circuitry.

Since the two signals are scaled the same and subtracted at their inputs, the outputs of IC's 1D and 2A will always be zero, unless either pressure sensing path malfunctions, in which case the two IC's will have an output which will switch one of the comparators (IC3 and IC4) if the preset threshold is exceeded (this is currently set at 10% difference). Which comparator switches, depends of which pressure signal is the largest. The comparator outputs are routed to IC5B which performs the logical OR function and

will provide a negative logic transition (high to low) if either comparator switches; this transition shuts down the system. The rest of the circuitry in the lower part of the drawing is not part of the pressure interlock and is not relevant to this discussion.

Selection of run segments: As previously mentioned a detailed pictorial depiction of the drive segments appears in the Appendix. The two segments chosen, have been given the following identifications:

Unstabilized segment: REN06
Stabilized segment: REN010

The REN06 segment is approximately 12 minutes long, the REN010 one approximately 10 minutes long. The difference in the two lengths is due to the need to find good "wraparound" spots, in order to minimize discontinuities at the point where the segment ends and restarts. Once the drive signal generator (a Hewlett-Packard 6942A Multiprogrammer) is loaded from the host computer (IBM PC or compatibles with parallel IEEE-488 interface) it functions in a stand-alone mode, recirculating the data for the duration of the experiment, and outputting it via its Digital to Analog (D/A) converters at 4 samples/second/channel, the same rate used during shipboard acquisition.

As seen in the spectral plots of the drive signals (Figures 2 through 7) the frequency range of interest lies between 0.06 Hz and 0.2 Hz. The worst case situation (0.6 Hz and a 10-minute segment) represents 36 time constants; with this separation, the recirculating signal should appear completely uncorrelated to the subjects.

The spectral plots were generated from raw (unscaled) data in order to determine the frequency content of the signals; consequently the magnitudes are related to an arbitrary reference and have no physical significance. The scale of the frequency axis is logarithmic to "spread" the region of interest. The lowest available scale of the spectrum analyzer used (Rockland 5820B) is 2 Hz and the region of interest almost disappears if a linear scale is used.

Drive signal transformations: At the low frequencies encountered in the selected drive segments (0.06 to 0.2 Hz), the response of the SMS is virtually frequency-independent, thus the only compensation needed is the double integration of the recorded heave acceleration, and single integration of the recorded pitch and roll angular rates. Additionally, the gain of the integrator(s) must be adjusted so the resulting position commands match the SMS scale factors. This adjustment is done using single-frequency test signals at the input of the appropriate integrator(s) as indicated below. The general procedure for heave is:

$a = A\sin wt$ where A in peak acceleration recorded in g's and w is the frequency in rad/s/s

The absolute displacement d is then obtained by double-integrating the above, or

$$d = (32.2A\sin wt)/w^{**}2$$

where 32.2 converts g's to ft/s/s

For a peak acceleration A, the peak displacement is $32.2A/w^{**}2$ and if the SMS scale factor is B, the position command to the SMS should be:

$$c = 32.2AB/w^{**}2$$

Pitch and roll are calibrated the same way, except that since rates (in deg./sec.) were recorded, only one integration is needed and

Roll angle, Pitch angle = AB/w where

A is peak angular rate in deg./sec
B is SMS scale factor in volts/deg.

The actual calibration of the SMS was performed using a 1 volt (peak) sine

wave @ 0.1 Hz. yielding the following:

Heave: Data is played back @ 10v/g and therefore the peak displacement is:

d = 3.22/(0.628)**2 = 8.165ft

The SMS heave scale factor is 0.8 volts/ft, therefore the required position command is:

c = 0.8 volts/ft * 8.165ft = 6.532 volts

resulting in the required path gain G of 6.532 volts/volt or 16.3db.

Pitch and roll: Data playback is 1 volt/deg/sec for the REN06 segment and 2 volt/deg/sec for the REN010 segment. The scale factor for these two axes is 0.5 volts/deg and applying these values to the formula, one obtains:

G(06) = 0.8 volts/volt or -1.94 db
G(010) = 1.6 volts/volt or 4..1 db

Implementation of the integrating networks:

A pure (in the theoretical sense) open-loop integrator is not realizable in the real world, because it has infinite gain at DC, i.e. any constant input level, no matter how small, integrates into a linear function of time. Because the heave channel has two integrations, the situation is even worse, as any bias at the input propagates as a quadratic function of time.

The solution to this dilemma is to replace the integrators with low-pass filters of the form:

$$F(s) = K/(Ts+1)$$

where K is a gain constant, T is the filter time constant and s is the Laplace variable. Rather than integrating biases forever (in reality until saturation), the biases integrate only up to the input value times the filter gain K. If T is selected such that the filter "break" frequency is well below the operating region, the filter will exhibit the characteristics of an integrator at the operating frequency region, i.e. will exhibit a constant attenuation slope of -6db/octave. A value of 7.5 seconds was selected for T for all four "integrators", and K was chosen to yield the gains computed in the previous section. The responses of the pitch/roll compensators (identical except for gain) are depicted in Figures 8 and 9 for REN06 and REN010 respectively. It is evident that in the operating region (>0.06 Hz or 0.38 rad/sec) the roll-off is indeed linear and at the proper slope. The gains at the calibration frequency of 0.1 Hz (0.628 rad/sec) are also seen to be correct

The heave channel was treated somewhat differently, because of the substantial path gain (16.7 db) needed to match the SMS's required input. A high-pass filter of the form:

$$F(s) = s/(T's+1)$$

was introduced in front of the low-pass filters. The numerator term performs the function of differentiation, and since the derivative of a constant is zero, any DC component at the input is blocked. The additional time constant T' is required because pure differentiation is not a real-world realizable function. In order not to disturb the response of the low-pass filters T' must be located at a frequency well below that of T. A T' value of 20 seconds was selected, placing it at 0.008 Hz. The frequency response of the resulting compensator is shown in Figure 10. It is evident that again the appropriate roll-off and gains obtain. The rolloff here is -12db/octave because there are two integrations involved.

The circuits that mechanize the necessary drive signal scaling and shaping are shown in Figure 11 which is largely selfdescriptive. The 2:1 gain switches on the pitch and roll output amplifiers provide the required gain change between REN06 and REN010 segments. The function of the similar switch on the heave channel will be described in the results section.

The somewhat elaborate procedure just described is necessary bacause it is the output of the SMS that must match the actual ship motion signals, because this is what the SMS rider feels. The command signals thus must be altered in whatever manner necessary to generate the desired SMS output, i.e. a close match to the measured at-sea motion.

Drive signal phase matching: As pointed out earlier, the time-coincidence of the three drive signals recorded onboard ship is altered by the dynamics of the SMS. The pitch and roll axes, being virtually identical, show no measureable differences in response, which shows a time lag of 0.45 seconds. The heave axis lag however is only 0.2 seconds, and in order to restore the phase relationship to that originally recorded, a lag of 0.25 seconds must be introduced in the heave drive signal. This was accomplished via the circuit shown in Figure 12, a fourth-order dead-time approximation. For the component values shown in the diagram delays of from 50 to 350 milliseconds are possible via the four adjustment potentiometers. A unique feature of this design is that all 4 potentiometers are ganged together and to a 10-turn indicator dial via a gear train. Time-delay adjustment thus can be accomplished via a single adjustment knob.

The circuit was adjusted for the required 0.25 second delay and its performance is shown in Figure 13.

Polarity match: The data acquisition package used onboard the USS Rentz recorded signals such that positive (+) voltages represent upward acceleration, forward pitch and roll to port. The SMS command circuitry was modified to that it responds to the drive signals in the same manner. The above polarities obtain if the package is installed in its preferred orientation. There have been trials in which this was not possible due to mounting constraints. Therefore it is important to verify the polarity match for every set of sea trial data.

RESULTS

Heave: For purposes of simulating the motions measured during the sea trials of the USS Rentz, the very low frequency content of the signals becomes important, because even for large heave excursions, the generated g levels are very low, generally less than 0.1 g's peak. At these levels, certain SMS artifacts that exist due to its design and which are very small in absolute terms, become discernible in the SMS response. The low frequencies observed must be characteristic of this and similar types of ships as data from a USS Boone (FFG-28) and from a USS Ingersoll (DD-990) trial are available at NAVBIODYNLAB and when reviewed, showed similar frequency responses to that of the USS Rentz.

Figure 14 shows the SMS's heave response to a 0.1 Hz, 0.1 g sinusoidal input. The first and third traces are the position and acceleration commands respectively, the second and fourth traces, the measured SMS responses to the commands. There is obviously no problem with the position response of the SMS, but the acceleration trace shows three types of distortion:

1. The "notches" at each end of the acceleration trace are caused by the static friction of the heave cylinder seal. At each direction reversal, this friction has to be overcome and when this happens the sudden "jerk" results. In layman's terms this is representative of the well known fact that in an environment where there is friction, it takes more force to get something to start to move than it takes to keep it going. The notches are of the order of 0.02 g's and are g-independent, therefore at higher g levels they become undiscernible.

2. The slight asymmetry between the positive and negative slopes of the curve.This is because the SMS heave axis piston is driven by the hydraulic pumps in one direction only, i.e. upward. Downward motion is obtained by letting the SMS "fall", pushing the hydraulic

fluid back to the supply. This distortion was reduced significantly by the addition of pressure feedback, as can be seen in Figure 15, which shows the SMS response to the same drive signal <u>without</u> pressure feedback.

3. The very slight wiggles all along the trace. This is probably caused by the hydraulic fluid; such a large volume of fluid is moved at high velocity that the flow is unlikely to be totally laminar, thus inducing a slight vibratory mode to the piston.

The acceleration signal shown in Figure 14 is unfiltered. The same signal passed through a 1 Hz low-pass filter is shown in Figure 16, which shows that the wiggles are totally gone indicating that the artifact in question is well beyond 1 Hz.

A 5 minute segment of the REN06 heave command is shown in Figure 17. Again the first and third traces are position and acceleration commands, the second and fourth the respective responses. It is obvious from this, that the fidelity of response is excellent. There is some "flattening" of the small oscillations, but in general the SMS tracks the position command very well. The acceleration traces also match very well, except for the the previously discussed distortion introduced by seal stiction.

The situation with the stabilized segment (REN010) half of which is shown in Figure 18, is somewhat different. The overall heave amplitude is significantly less than that for the REN06 segment. This is not surprising, since except for the area along the longitudinal centerline passing through the center of gravity of the ship, roll induces a heave component. The problem with this profile is that some of the amplitude variations are so small that threshold effects begin to appear. Examples of this are highlighted by the two arrows on the position trace; these show a complete stoppage of motion for several seconds. Because of the threshold effect, the overall position envelope is also somewhat smaller than the command envelope.

A solution to this problem is depicted in Figure 19, which shows the SMS response when the acceleration command is boosted approximately 18% from the values measured onboard ship. Although the stops are not totally eliminated, the situation is greatly improved as is the overall trajectory fidelity. Obviously, as shown on Figure 19, the SMS acceleration is somewhat higher than that measured at sea, but this is a less significant aberration than having the simulator stop its vertical motion for significant lengths of time. The boost of the REN010 signal is implemented via a switch on the output amplifier of the heave compensator (Figure 11). The boost feature can easily be deleted if necessary.

<u>Roll</u>: Since roll stabilization is the proposed independent variable for the initial set of SMS experiments, it is obvious that roll conditions must drive the selection of the segments to be used in the experiment. The segment REN06 was recorded while the ship was dead in the water in seas with equivalent wave heights to those observed during the recording of REN010, the stabilized segment. The specific segment chosen has roll angles of up to 13 degrees peak, near the limit of the SMS's capability of 15 degrees peak. A 5-minute segment of REN06 roll is shown in Figure 20 (the sequence here is different from previous figures shown). The top trace is roll rate as measured in the SMS, the second is the roll rate as measured onboard ship. The third and fourth traces are roll position command and SMS roll position respectively. Again, the fidelity of response is excellent overall, but one can see on the top trace (roll rate measured in the SMS) that near the zero crossings exist what appear to be small discontinuities. This can be better seen in Figure 21 where a small test signal was used to exaggerate the distortion. In this figure, the bottom trace is the SMS-measured roll rate. The discontinuity exists because the center of gravity (c.g.) of the cab/carriage

combination is well above the gimbals: As the SMS superstructure nears the end of travel, the dynamic loading on all compliances changes directions. The pitch and roll gimbals are driven by linear double-acting hydraulic actuators which either push or pull on a lever arm offset from the gimbals' centerline. For example, starting from a full starboard tilt, the roll actuator pushes against the load presented by the cab-carriage combination, until the port extreme is reached, at which region the load reverses and the actuator now begins to pull the load . When this occurs, all slacks, compliances etc. reverse in sense, and the discontinuities shown in Figures 20 and 21 result.

This phenomenon is much more prevalent in roll than in pitch, because of the roll-over-pitch design of the carriage. While the pitch gimbal attaches directly to the carriage, the roll one is mounted atop the pitch gimbal. Thus, unlike pitch, the roll axis is affected by compliances in both axes. It should be noted that not all of the distortion observed is necessarily real: Part of it could be measurement error caused by mechanical imperfections in the feedback assembly, but this is difficult to isolate and quantify.

A 5-minute segment of the REN010 condition is shown in Figure 22. The top two traces are roll angle command and roll angle respectively, the bottom two, roll rates measured onboard ship and the SMS respectively. The significant departure from the quasi-sinusoidal response shown in Figure 20 for REN06 is apparently caused by the fin stabilizers. Review of other unstabilized run segments when the USS Rentz was underway, indicate a response nearer REN06 than REN010.

The pitch signals for the two conditions are shown in Figures 23 and 24, the top trace being the pitch rate as recorded on the ship, the next two are pitch command and position respectively. At the time of data collection, the SMS pitch rate sensor was not functional, thus rate signals were not recorded. For both conditions, the total pitch angles seem equivalent, and are rather small.

SUMMARY

1. A stepwise procedure for optimizing the Ship Motion Simulator (SMS) to properly respond to specific ship motion profiles has been presented. The SMS was driven on all three axes with selected segments from a sea trial conducted on a FFG7-class frigate (USS Rentz), and the resulting motion was documented and compared with the drive signals. The capability of the SMS to replicate actual ship motion, including preservation of phase relationships is readily evident from these comparisons.

2. An historical overview of the SMS and of the improvements added after it was moved to its present site have also been presented. Reports and papers documenting significant research products resulting from SMS use have been cited.

3. Finally, in answer to the question posed by the title of this report, i.e. "can the Ship Motion Simulator simulate ship motion", the answer is. Yes, very well indeed!

CONCLUDING REMARKS

1. The drive signal generator, based on the Hewlett-Packard 6942A Multiprogrammer is an effective and easy to use device for playing back sea trial data. The system is quite universal and is able to play back data acquired digitally in almost any standard format. Additionally, the SMS facility has a dedicated analog instrumentation recorder that can play back any data acquired in IRIG proportional-bandwidth format.

2. Circuitry to provide scaling and shaping of the drive signals was designed, built and its effectiveness verified. Presently it is fairly specific to the current application of the SMS, but more general and flexible circuitry can and

will be designed. This is a candidate for interactive computer-based optimization techniques.

3. The SMS and the staff of NAVBIODYNLAB together represent an unique capability to perform motion research that is directly applicable to real Navy motion environments. This capability is unique within the Department of the Navy.

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The work described in this report would not have been possible without using actual sea trial data. Mr. Dave Knouse of NAVBIODYNLAB is almost solely responsible for collecting this data, often at great personal disconfort. He configured the hardware and developed the acquisition and display (scaling and plotting) software for the sea trials. Later he configured the hardware and developed the software for data playback in the SMS. The author wold like to personally thank Mr. Knouse for his diligent, professional efforts.

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FIGURE 1 - Pressure Feedback Loop Circuitry

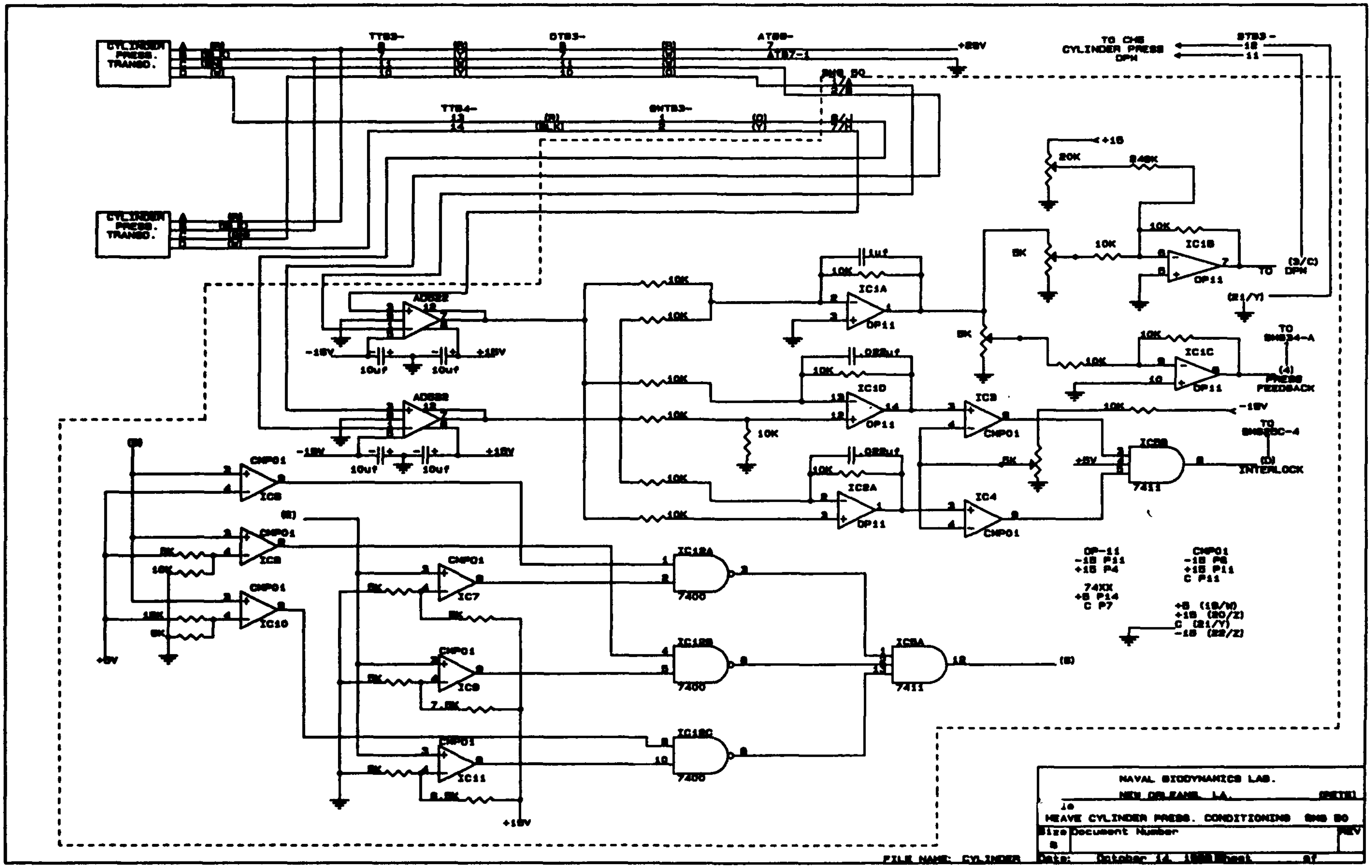
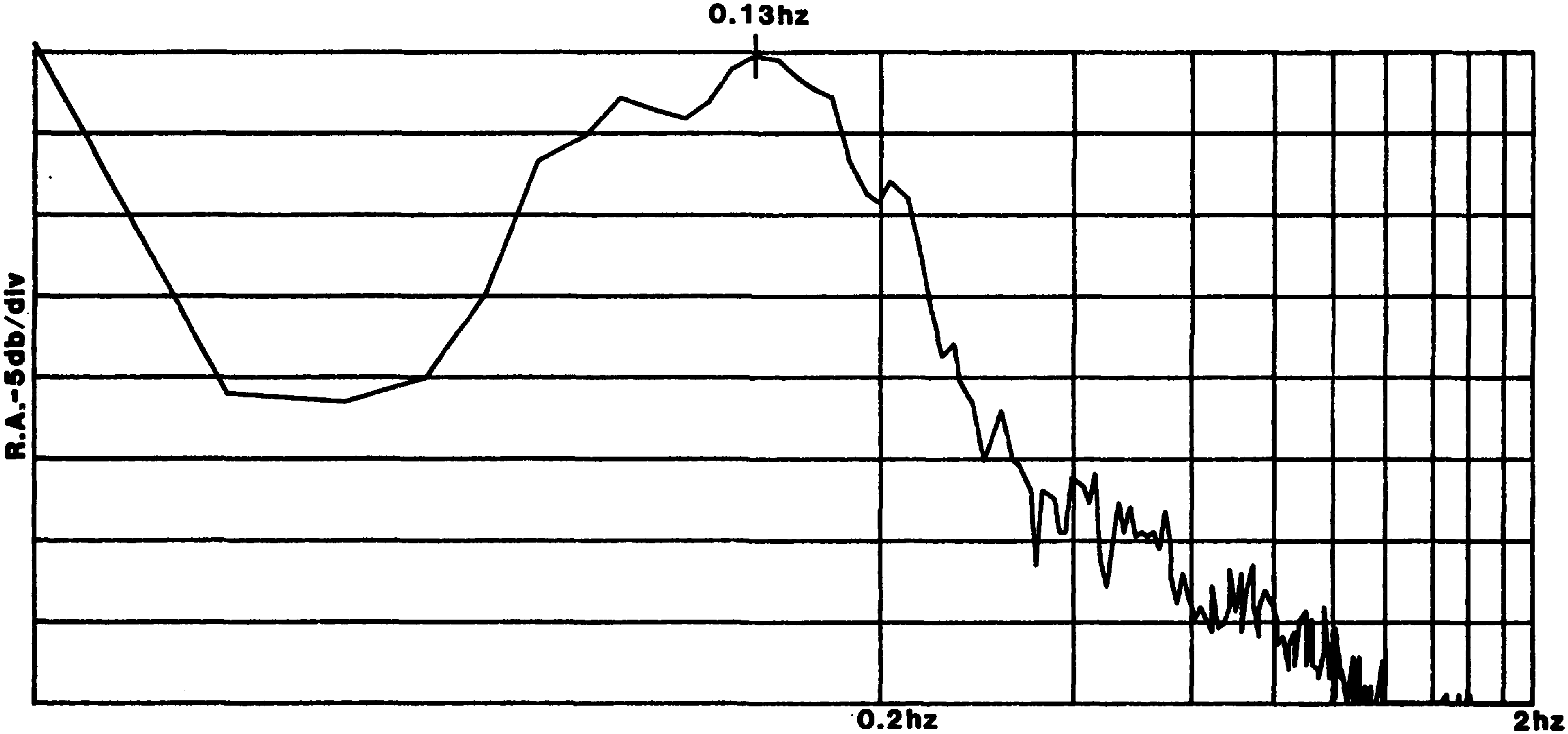


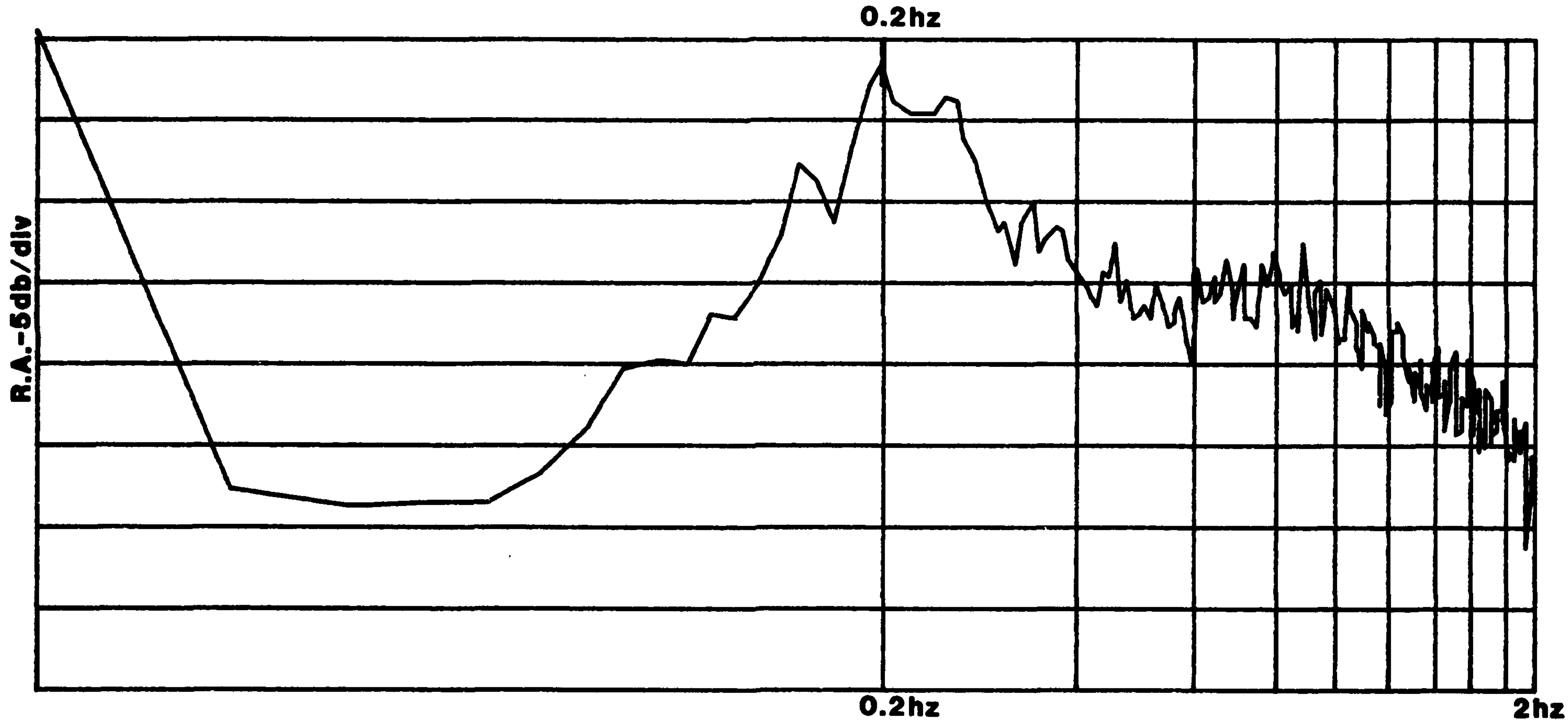
FIGURE 2 - Frequency Spectrum - Heave Accel. (RENO6)



PWR SPECT A :- 31.5dBV 0.13 HZ N: 8 F:.01HZ

SPAN: 0.000HZ - 2.000HZ SN: 20dBV FS: - 30.50dBV 5dB/

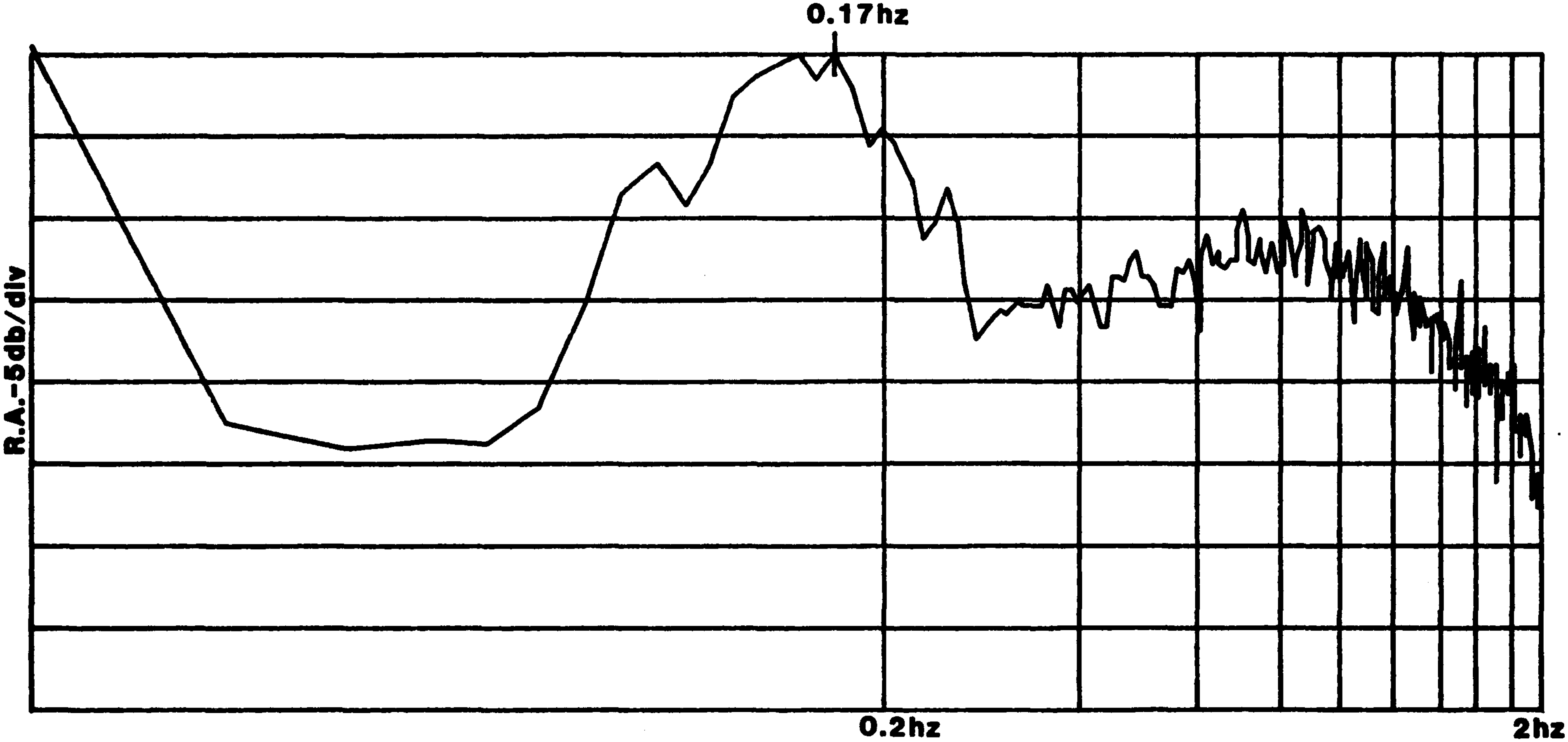
FIGURE 3 - Frequency Spectrum - Heave Accel. (RENO10)



PWR SPECT A :- 38.5dBV 0.20 HZ N: 8 F:.01HZ

SPAN: 0.000HZ - 2.000HZ SN: 20dBV FS:- 36.00dBV 5dB/

FIGURE 4 - Frequency Spectrum - Pitch Vel. (RENO6)

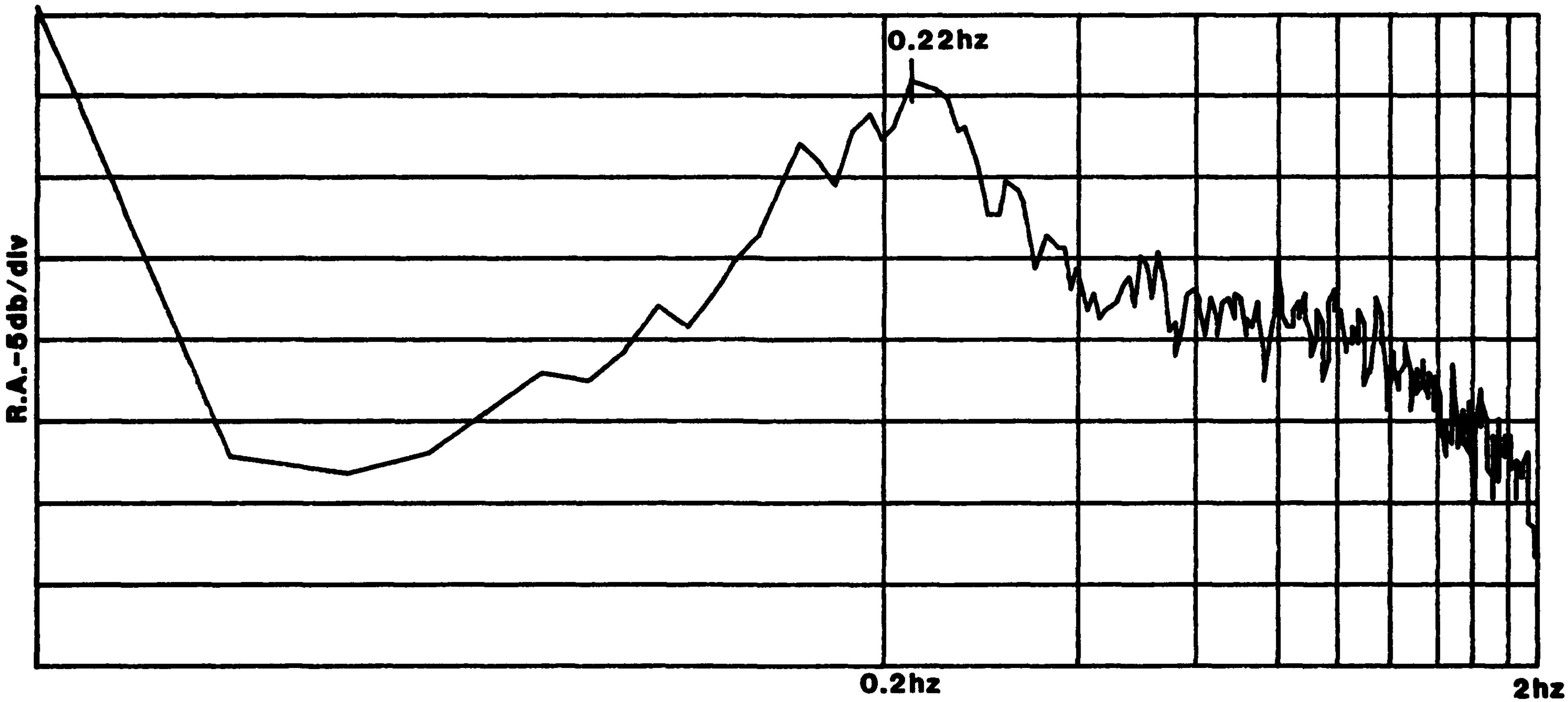


PWR SPECT A : - 38.8dBV 0.17 HZ N: 8 P: .01HZ

SPAN: 0.000HZ - 2.000HZ SN: 20dBV FS: - 38.00dBV 5dB/

5

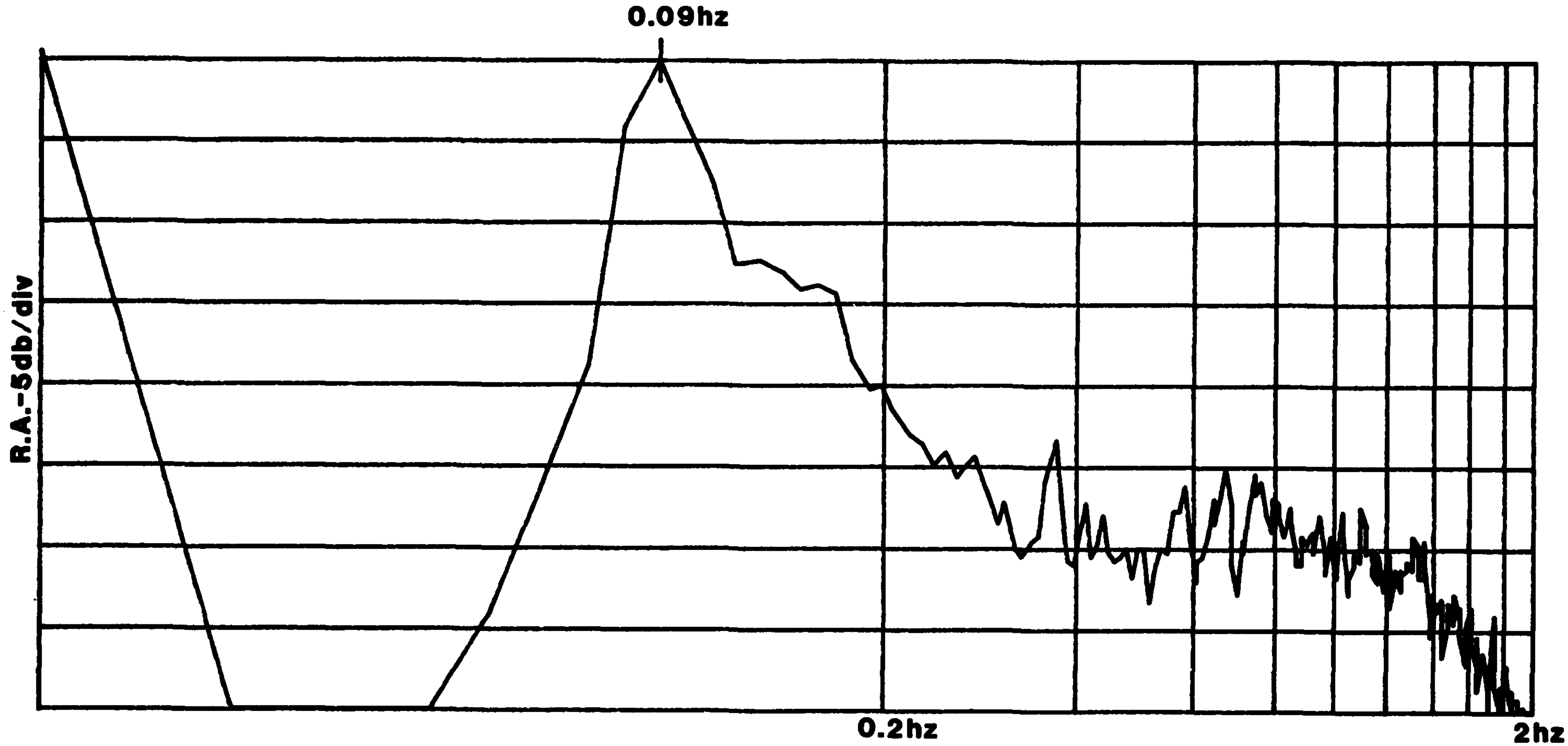
FIGURE 5 - Frequency Spectrum - Pitch Vel. (RENO10)



PWR SPECT A : - 41.0dBV 0.22 HZ N: 8 P: .01HZ

SPAN: 0.000HZ - 2.000HZ SN: 20dBV FS: - 36.00dBV 5dB/

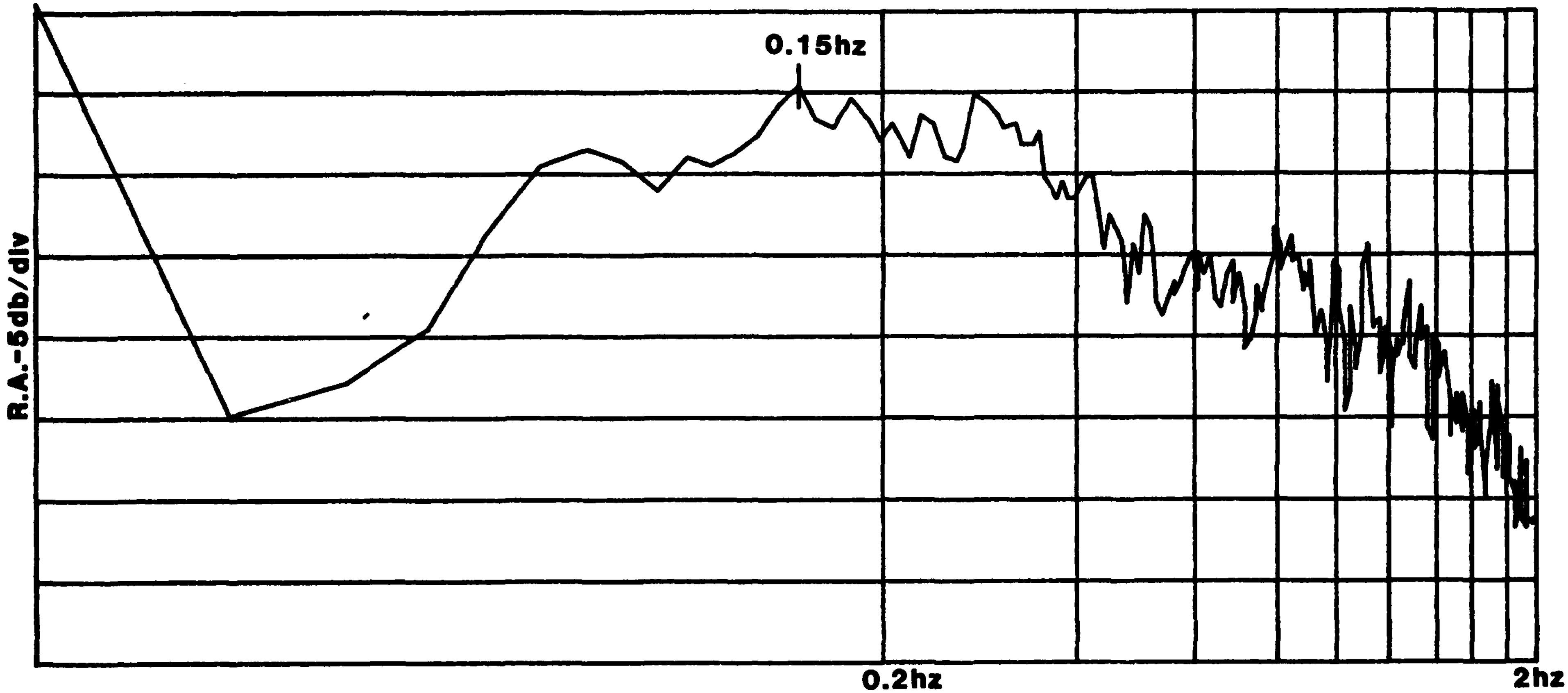
FIGURE 6 - Frequency Spectrum - Roll Vel. (REN06)



PWR SPECT A : - 21.4dBV 0.09 HZ N: 8 P: .01HZ

SPAN: 0.000HZ - 2.000HZ SN: 20dBV FS: - 20.50dBV 5dB/

FIGURE 7 - Frequency Spectrum - Roll Vel. (RENO10)



PWR SPECT A : - 41.3dBV 0.15 HZ N: 8 F: .01HZ

SPAN: 0.000HZ - 2.000HZ SN: 20dBV FS: - 36.00dBV 5dB/

FIGURE 8 OPEN-LOOP FREQUENCY RESPONSE PLOTS

Gil Willems 12-14-88 Pitch/Roll Compensator (RENO8)

3.85/(7.5+1)

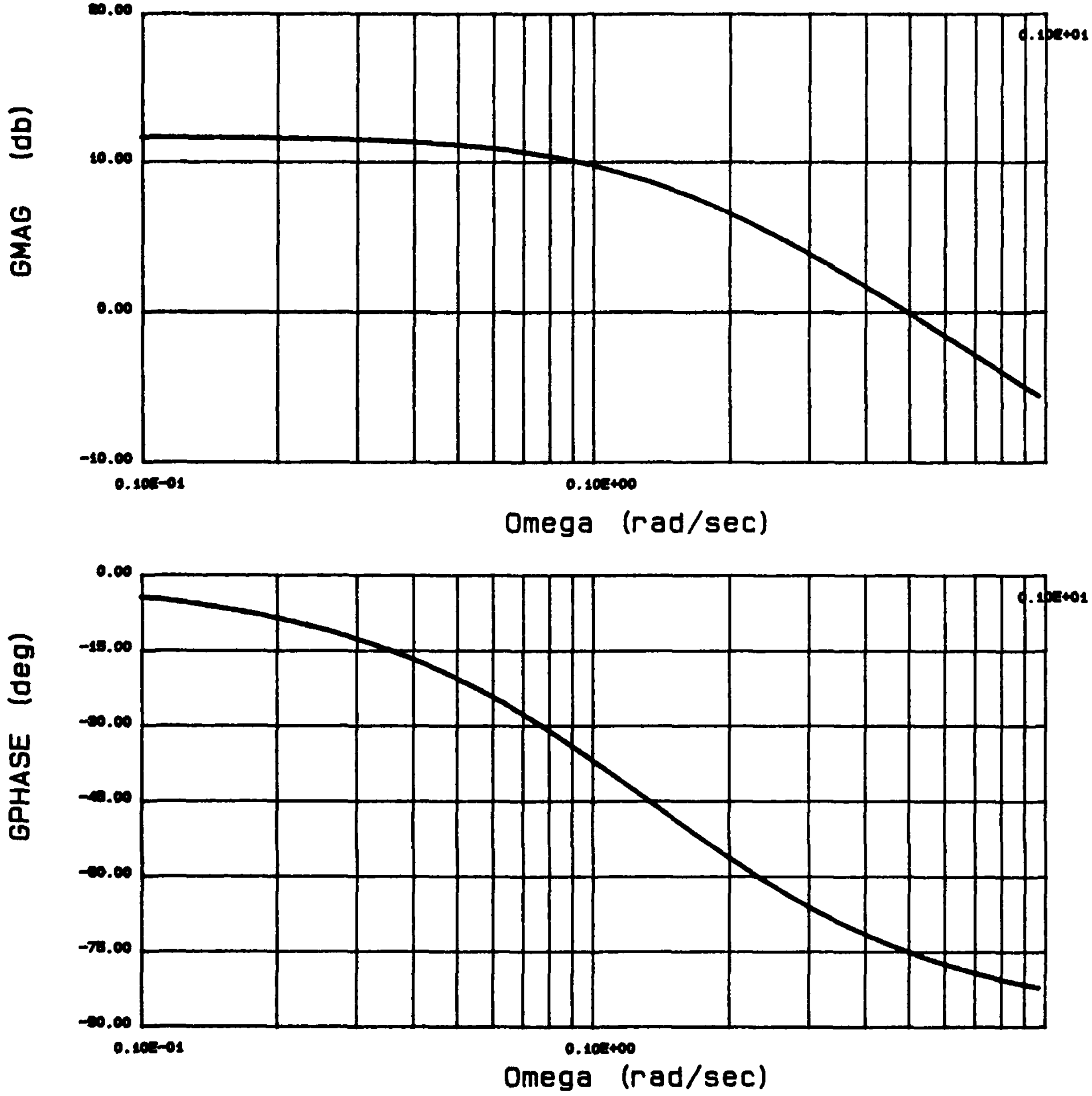


FIGURE 9 OPEN-LOOP FREQUENCY RESPONSE PLOTS

Gil Willems 12-14-88 Pitch/Roll Compensator (REN10)

7.7/(7.5s+1)

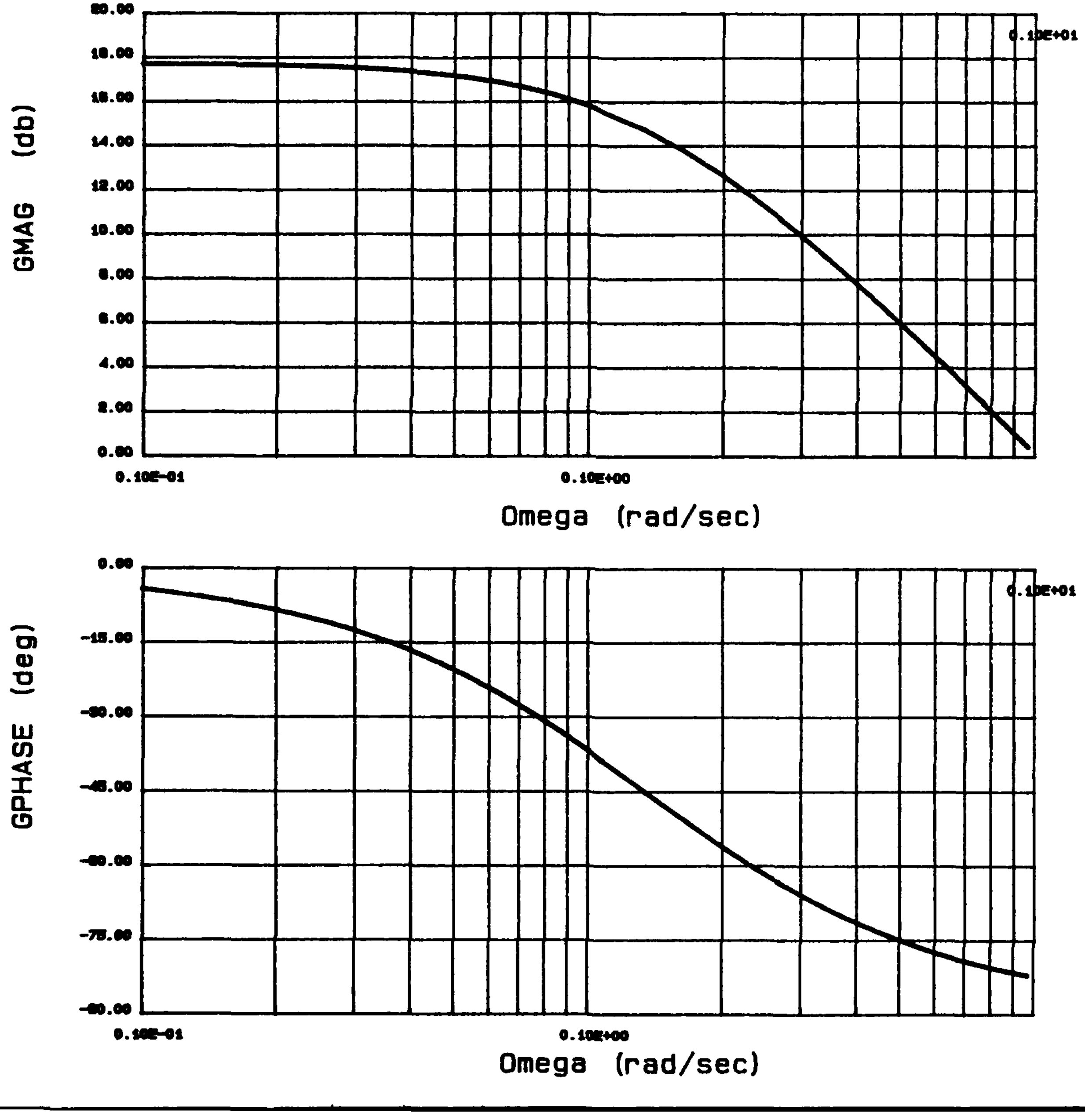


FIGURE 10 OPEN-LOOP FREQUENCY RESPONSE PLOTS

Gil Willems 12-14-88 Heave Compensator

3000s/(20s+1) (7.5s+1) (7.5s+1)

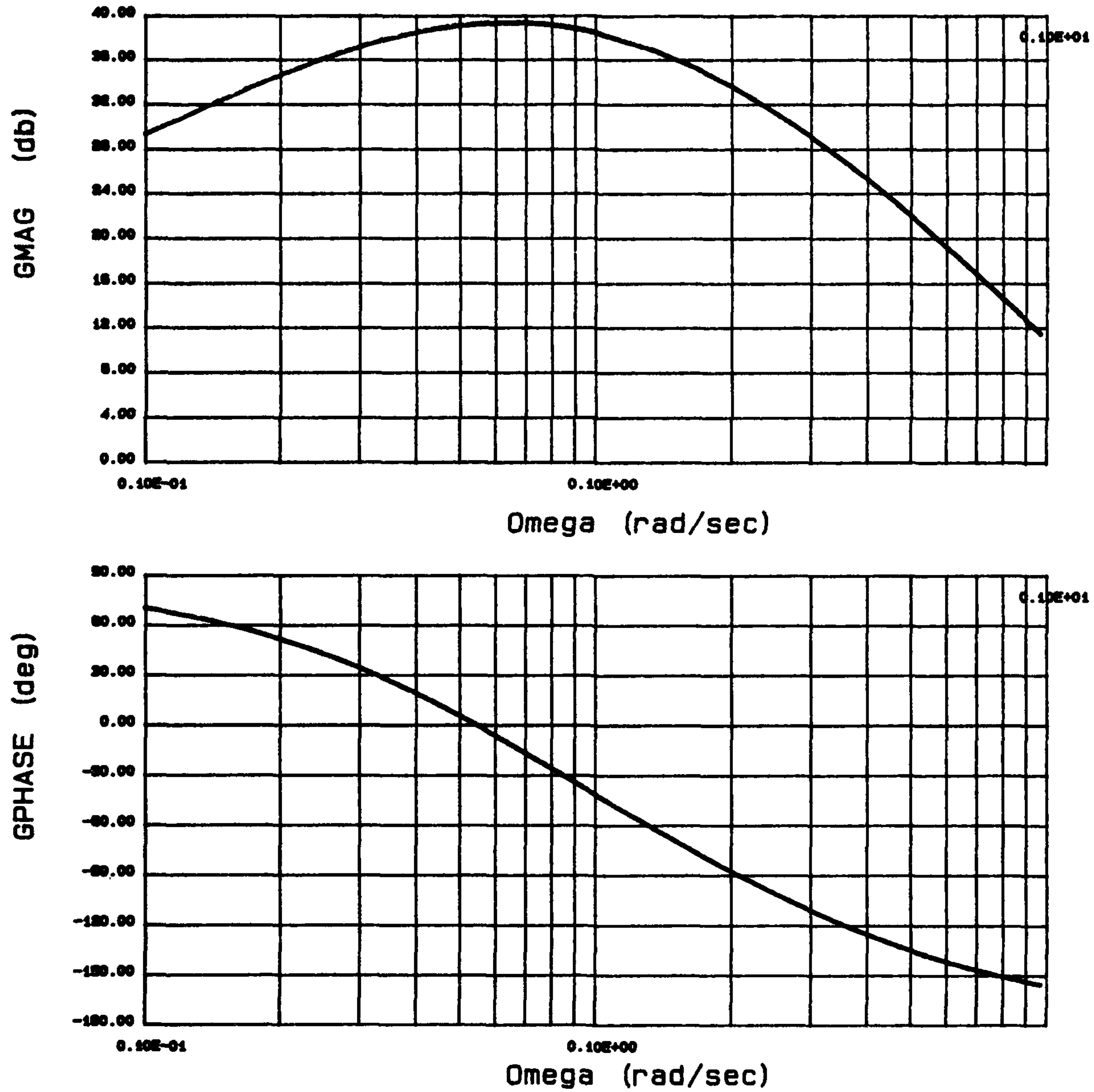


FIGURE 11 - Compensator Circuitry

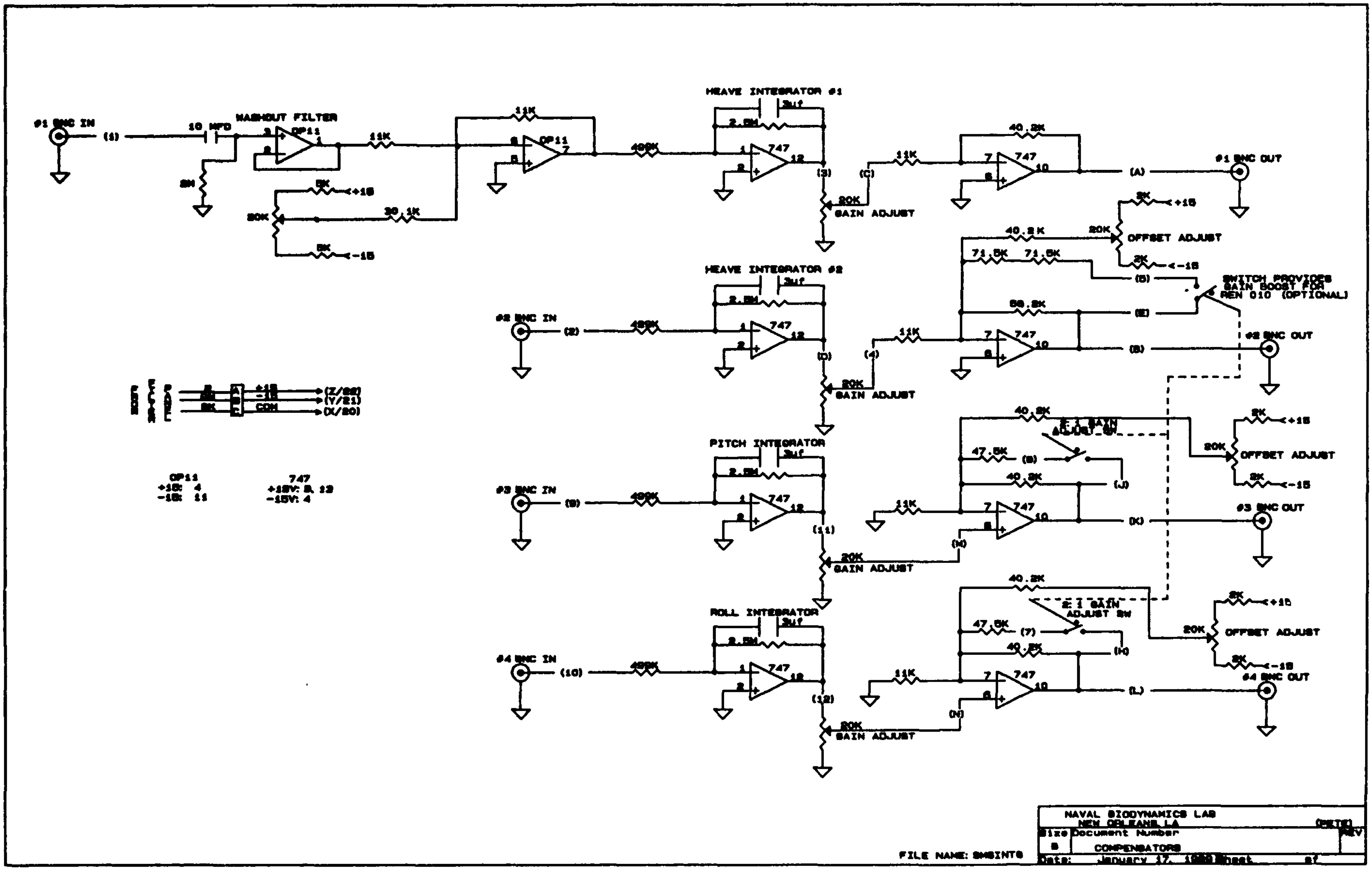


FIGURE 12 - Heave Time Delay

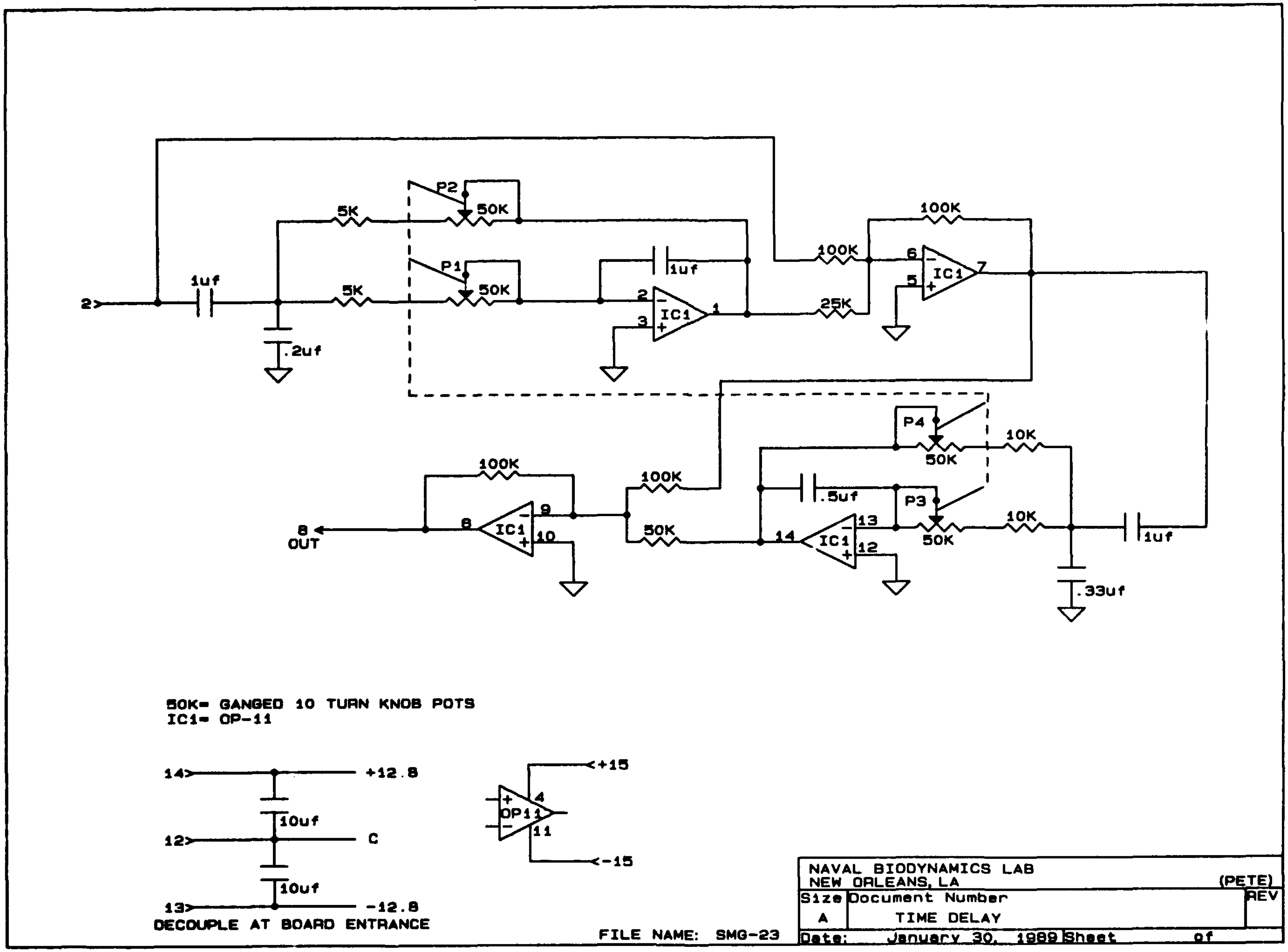


FIGURE 13 - Time Response of Delay Circuit

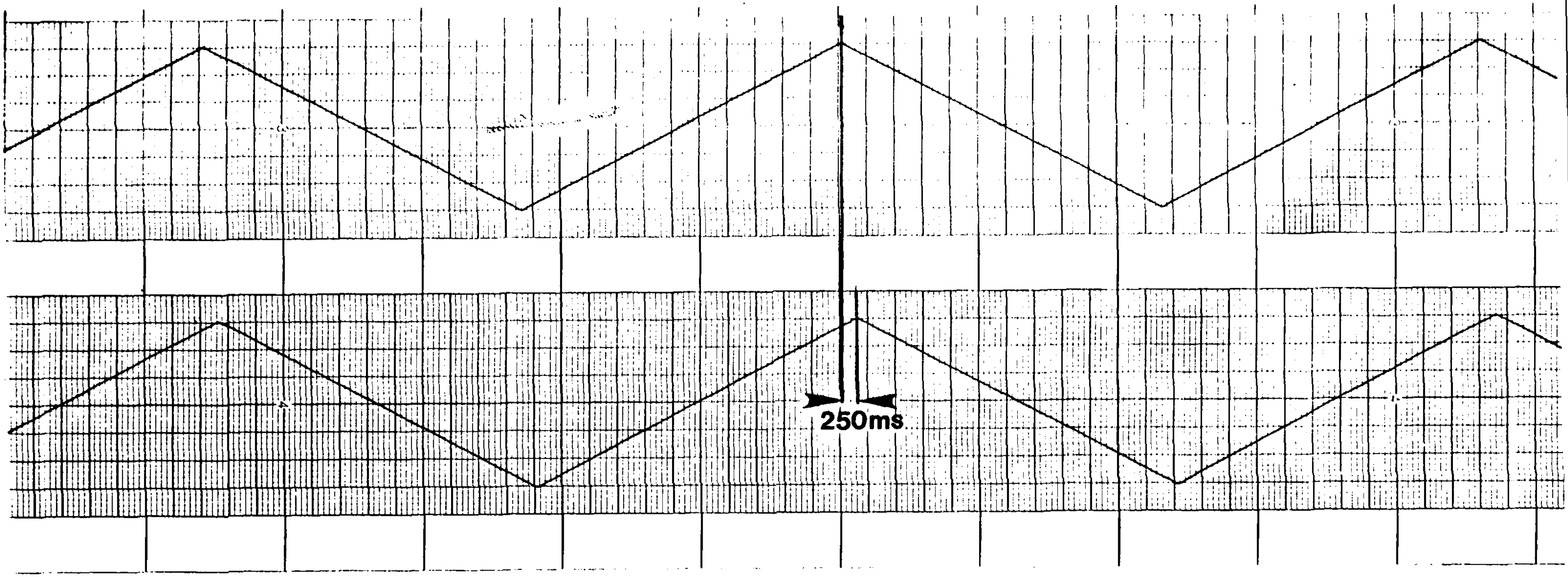


FIGURE 14 - Heave Response to Test Signal (No Filter)

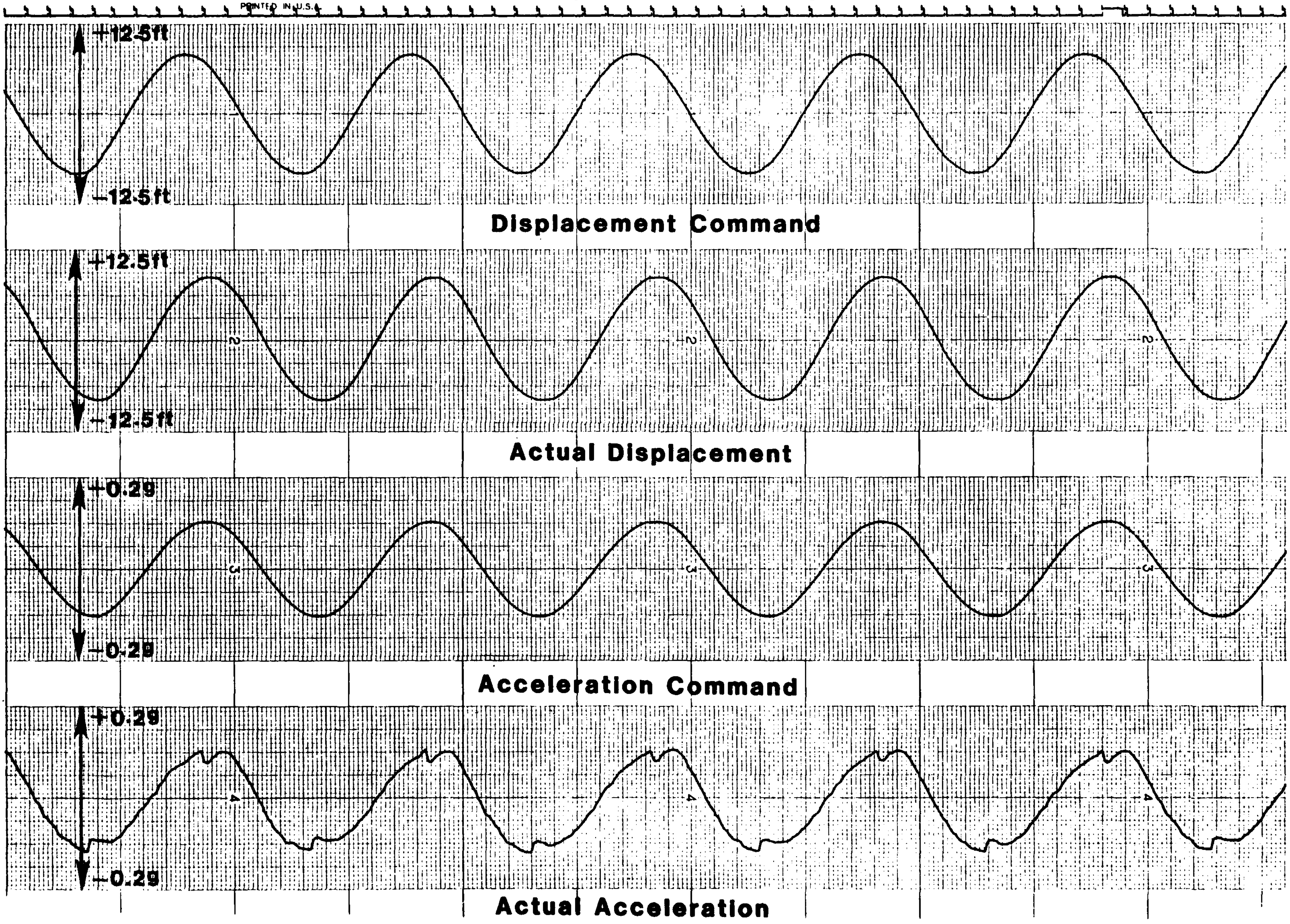


FIGURE 15 - Heave Response to Test Signal (No Pressure Feedback)

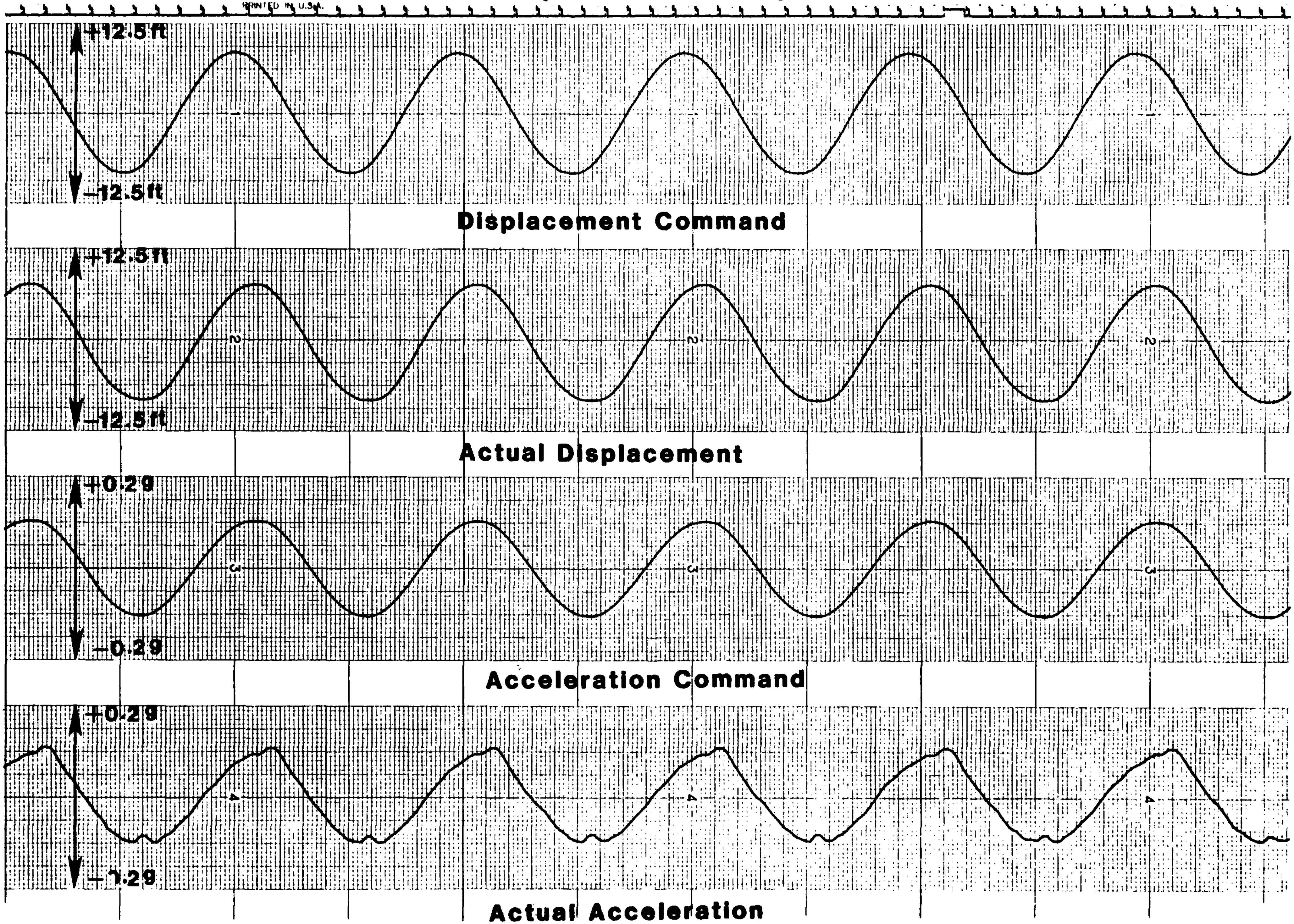


FIGURE 16 - Heave Response to Test Signal (With Pressure Feedback and Filter)

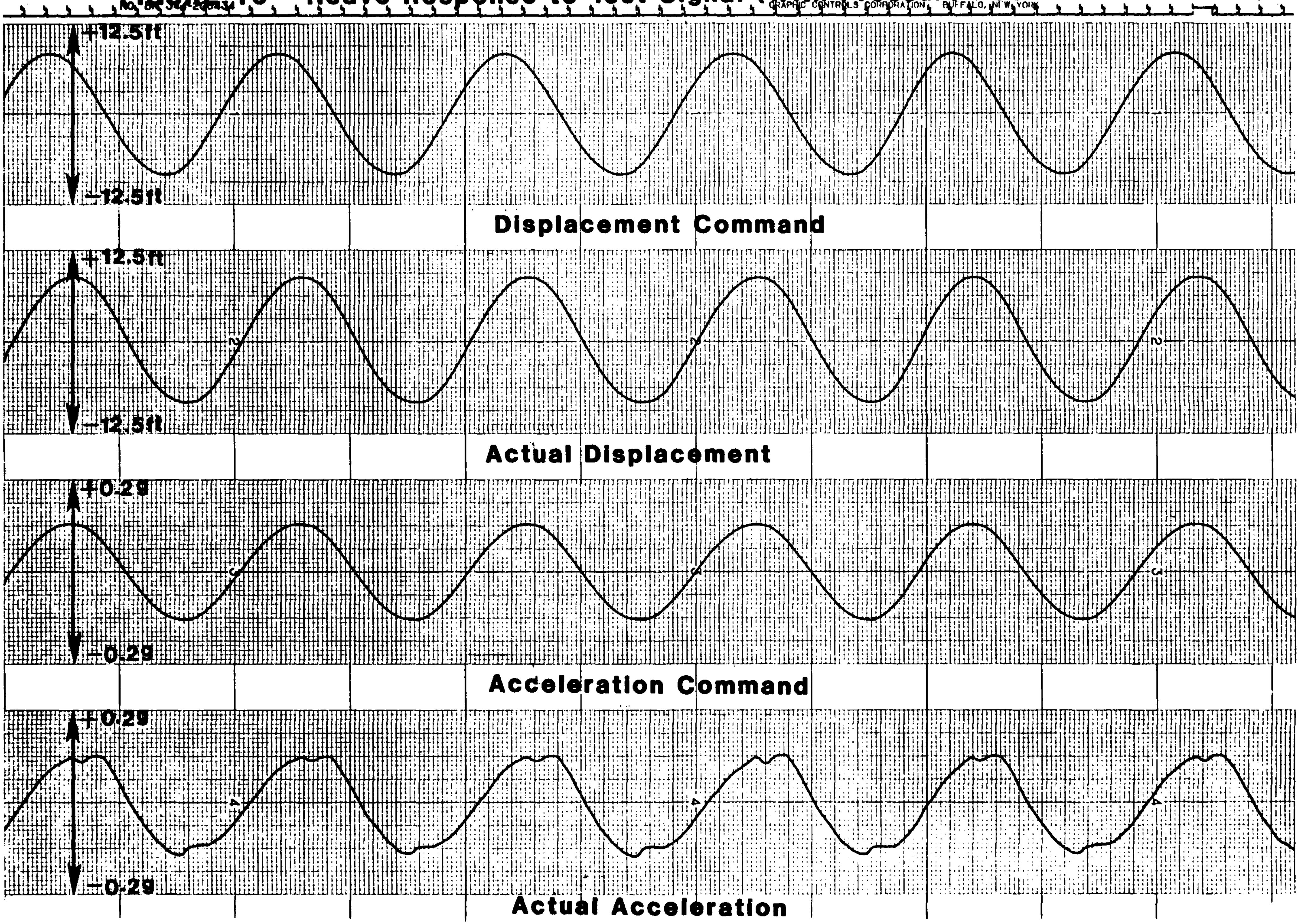


FIGURE 17 - Heave Response to RENO6 Signal

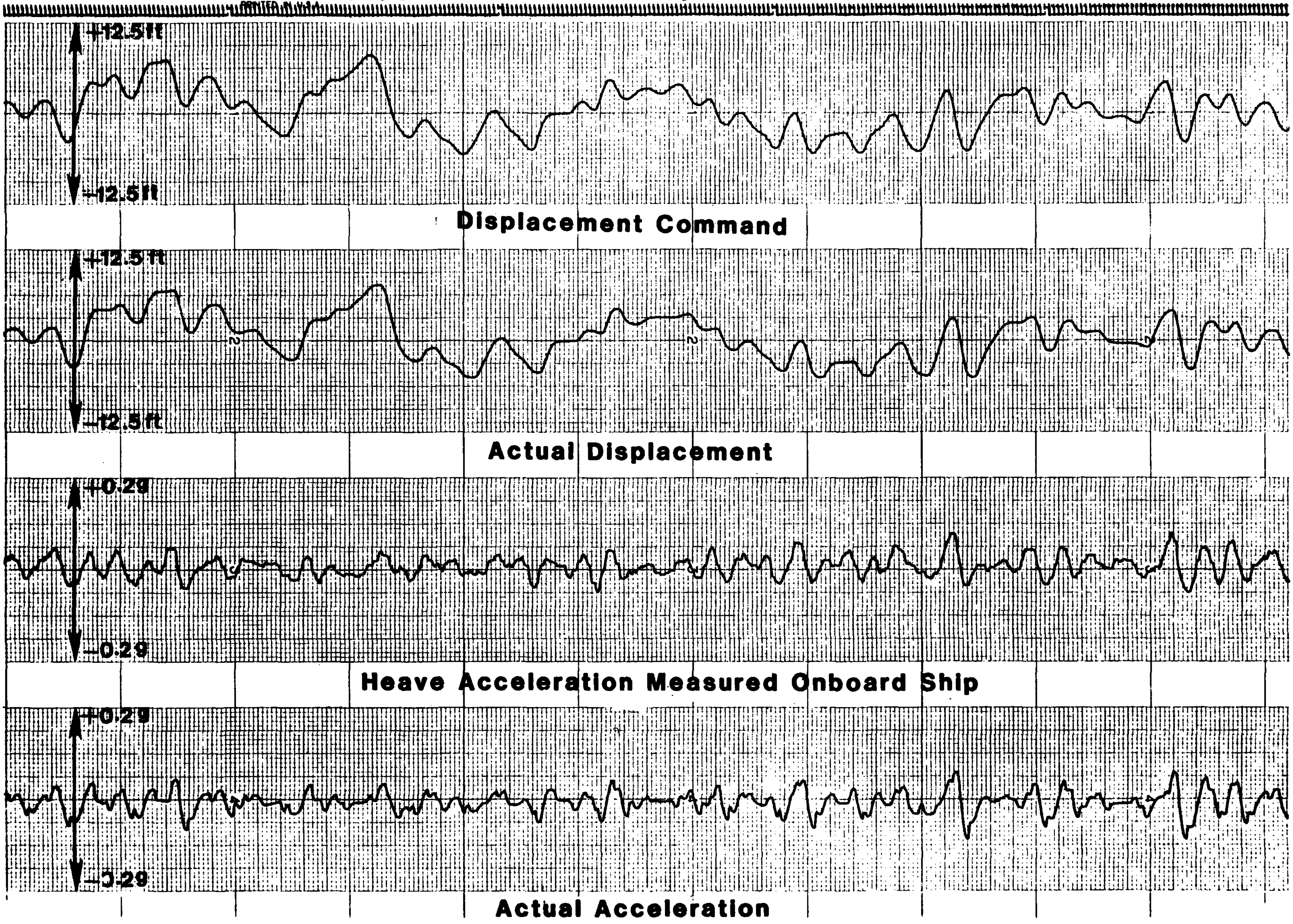


FIGURE 18 - Heave Response to REN010 Signal

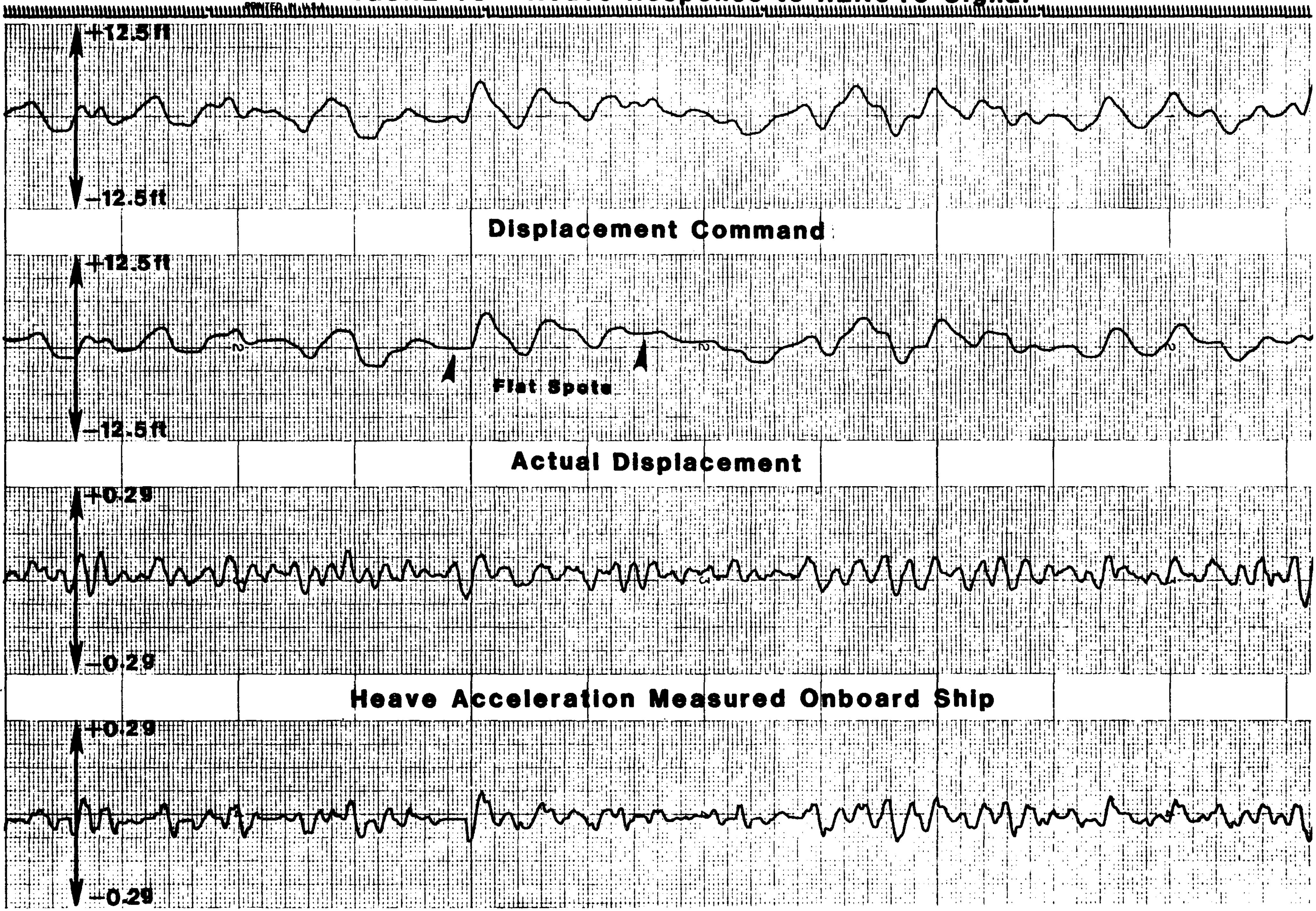


FIGURE 19 - Heave Response to Boosted RENO10 Signal

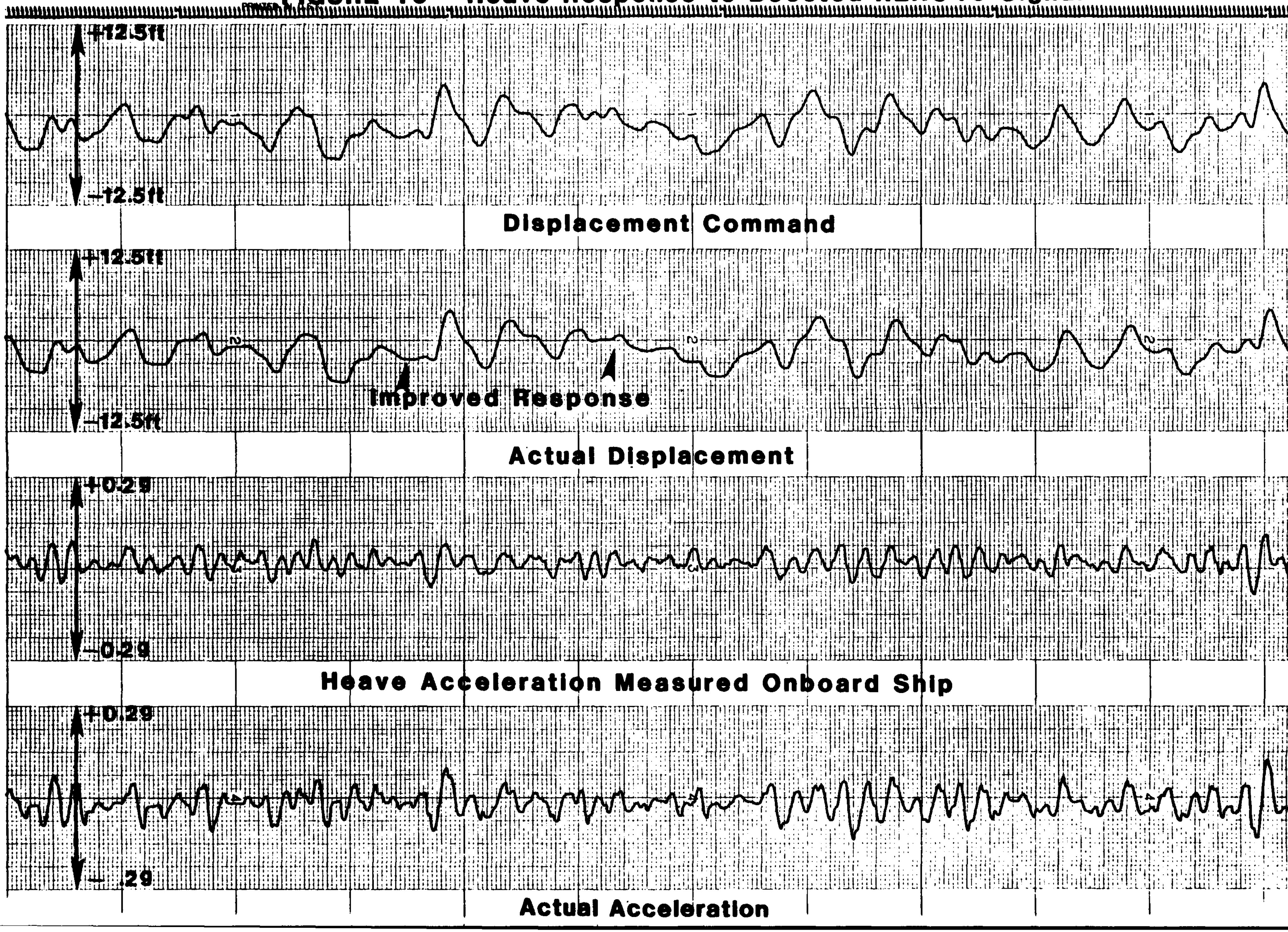


FIGURE 20 - Roll Response to RENO6 Signal

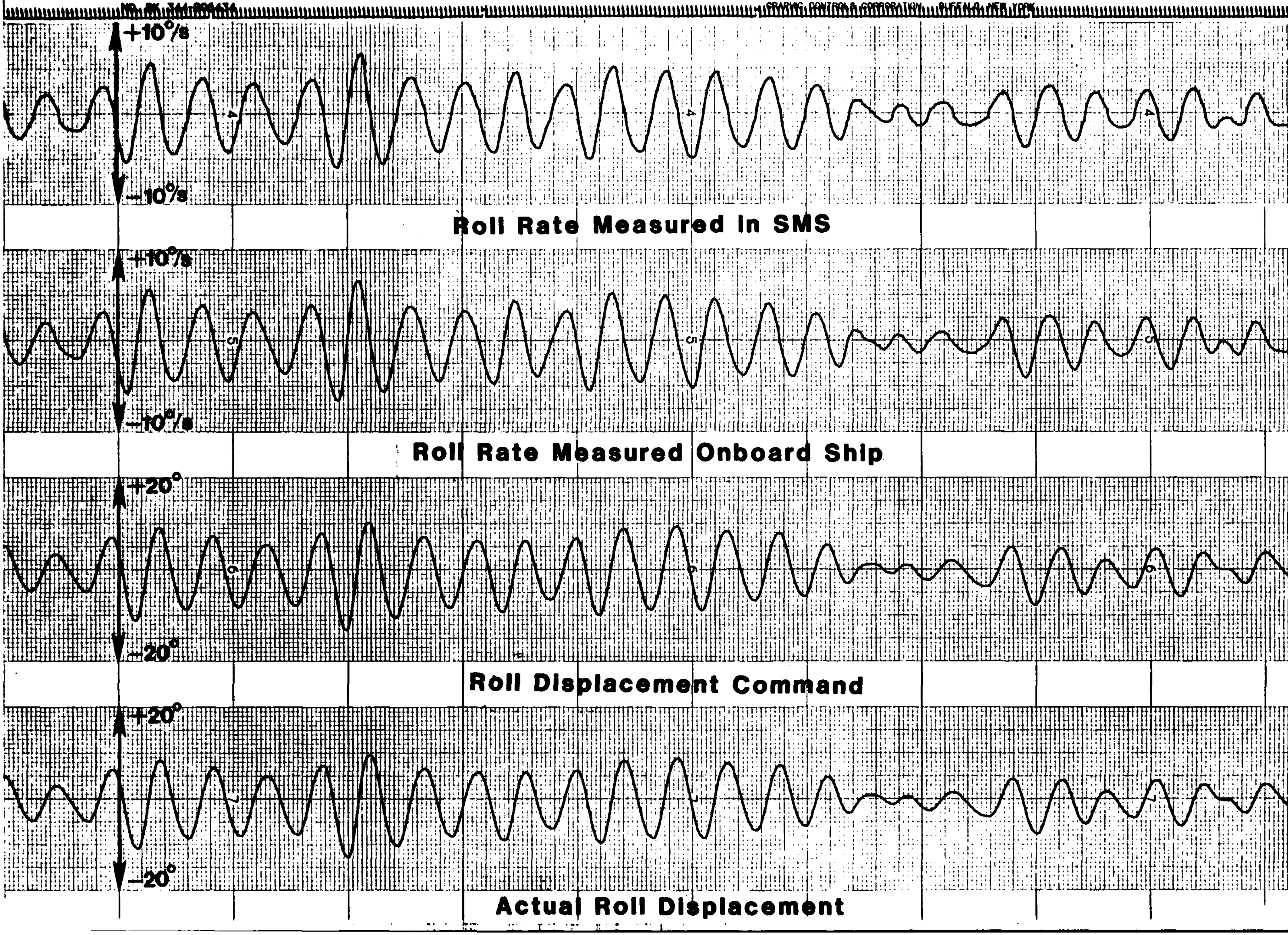


FIGURE 21 - Roll Response to Test Signal

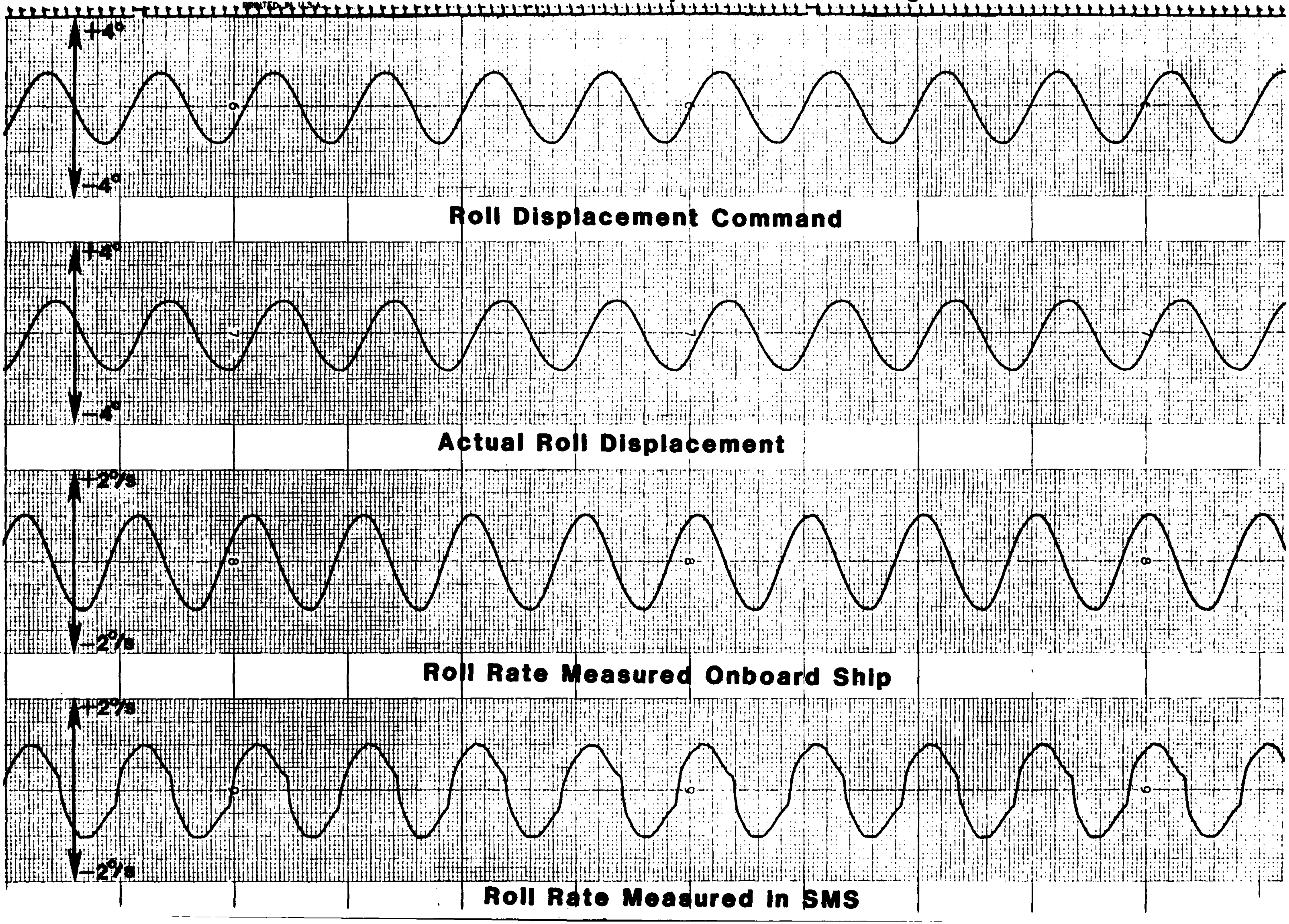


FIGURE 22 - Roll Response to REN010 Signal

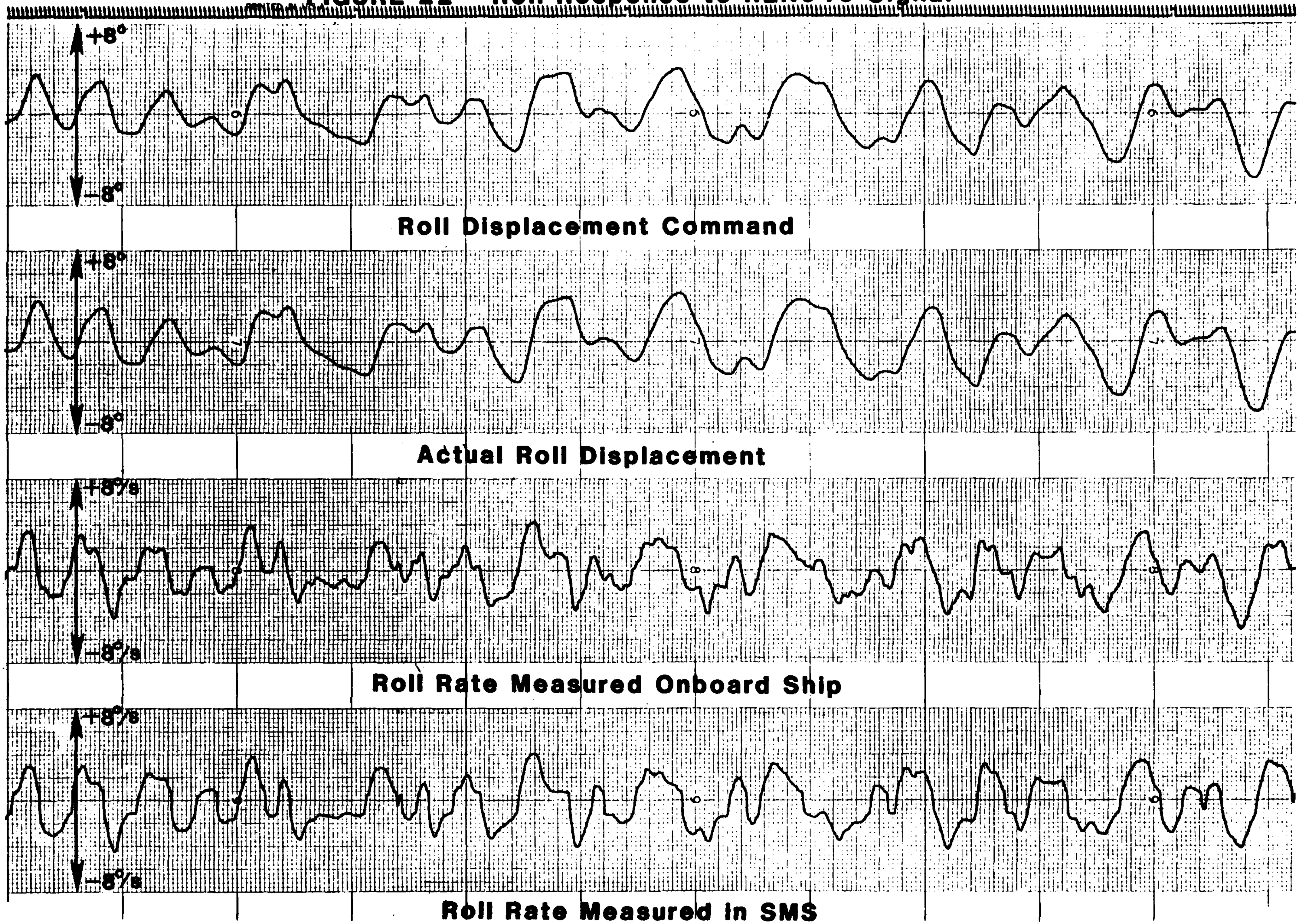


FIGURE 23 - Pitch Response to REN06 Signal

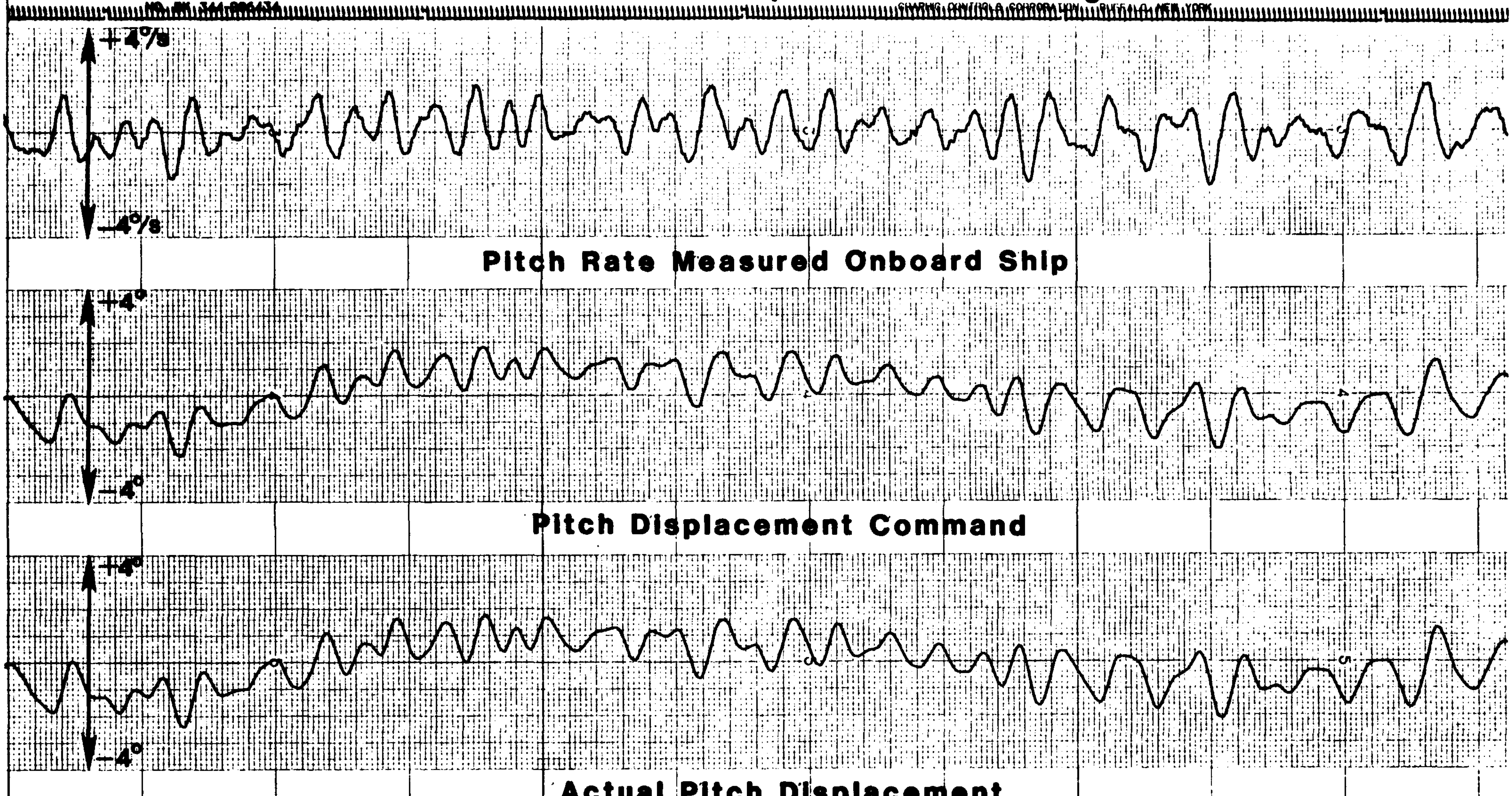
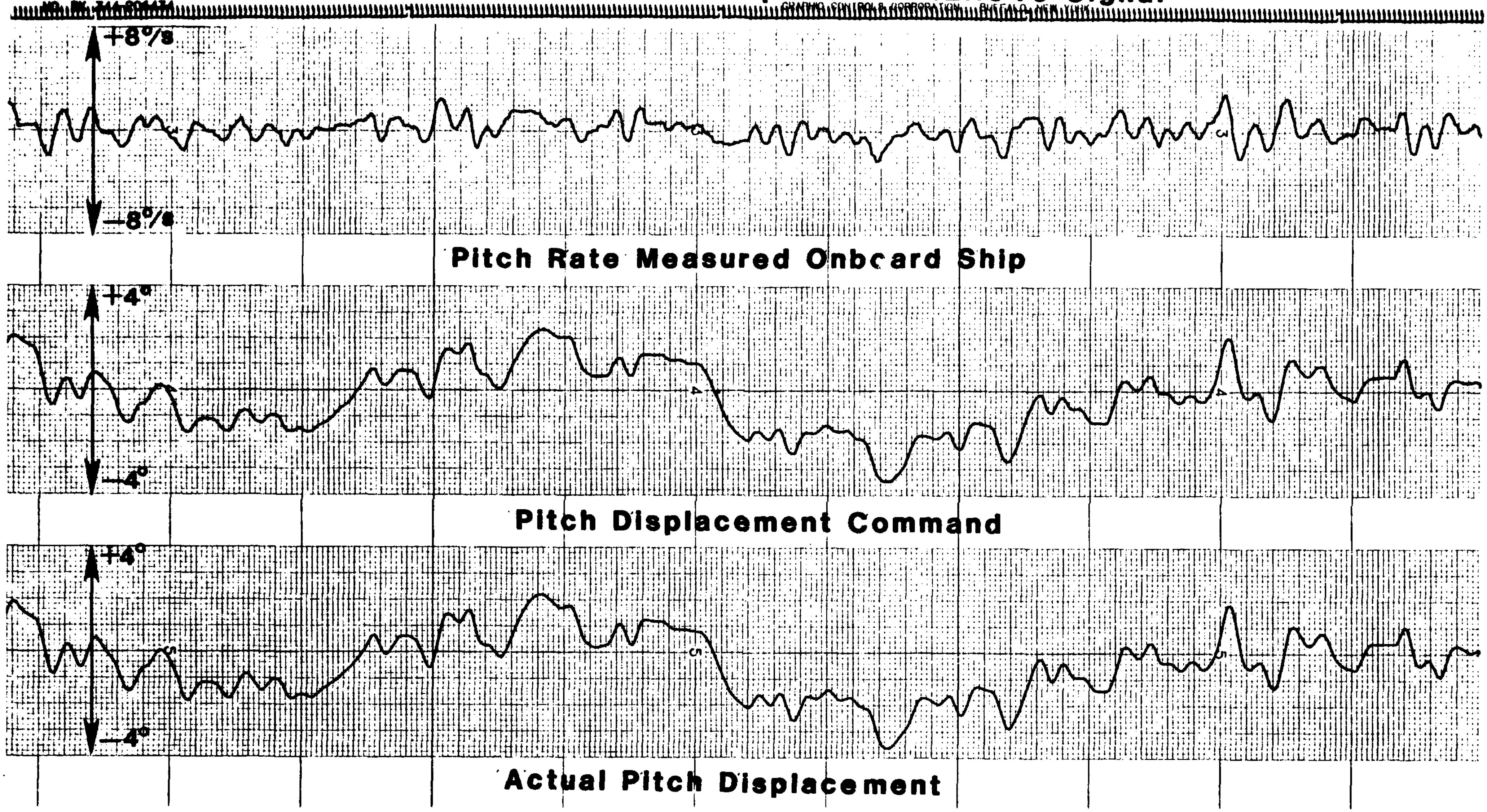


FIGURE 24 - Pitch Response to REN010 Signal



APPENDIX

The data presented in this Appendix are a collection of tables and plots for the two selected run segments, generated during the sea trials of the USS Rentz as well as "snapshot" plots of the entire run segments. Tables A-I and A-II present a summary of the environmental conditions and data acquisition parameters. Figures A-1 through A-4 show one-minute samples of the collected data at the beginning and end of the REN06 segment. Figures A-5 through A-7 show the entire run segment for the three signals being used to drive the SMS.

Finally, Figures A-8 through A-14 present the data plots just described, for the REN010 segment.

TABLE A-I

SUMMARY OF RUN: REN006

DATE..................03-19-1986
START TIME...........09:45:00
END TIME.............10:45:00
SAMPLE RATE (S/S/C).. 4
A/D SYSTEM GAIN...... 4
FIRST CHANNEL........ 0
LAST CHANNEL......... 5
OF RECS WRITTEN.... 3996

CHANNEL ASSIGNMENTS	SHIP & WEATHER INFO.
1. Pitch rate	Ship's heading: 0 - 10deg.
2. Roll rate	Ship's speed: 0 - 10K.
3. Yaw rate	Wind direction: 0 - 10 deg.
4. Heave Accel.	Wind speed: 5 - 15k.
5. Transverse Accel.	Wave direction: 350 - 80 deg.
6. Longitudinal Accel.	Wave height: 4 - 10 ft.

DIW FOR FIRST 20 MIN. OF RUN AND FINAL 25 MIN. OF RUN

FIGURE A-1 One-Minute Segment at Start of RENO6 Test

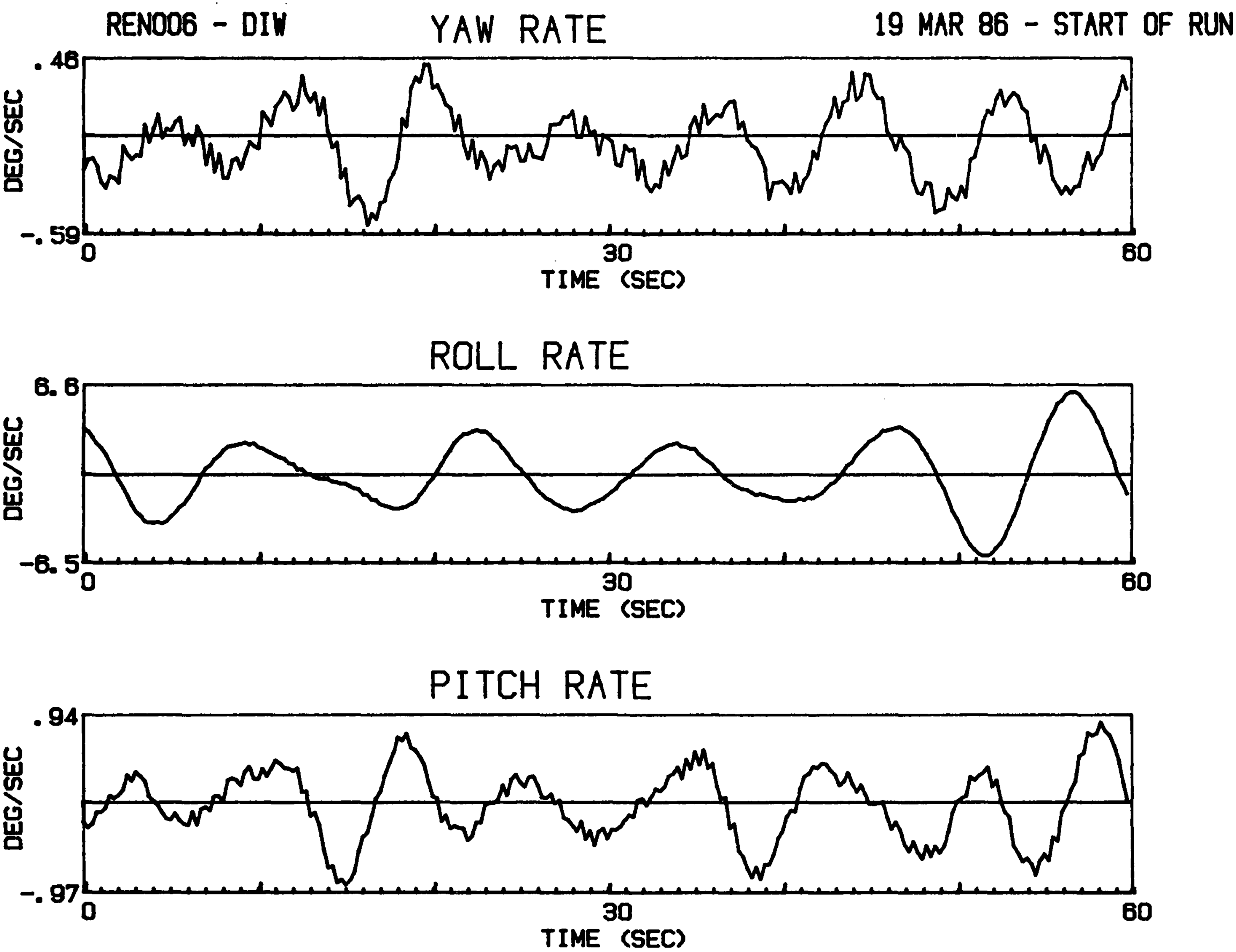


FIGURE A-2 One-Minute Segment at Start of RENO6 Test

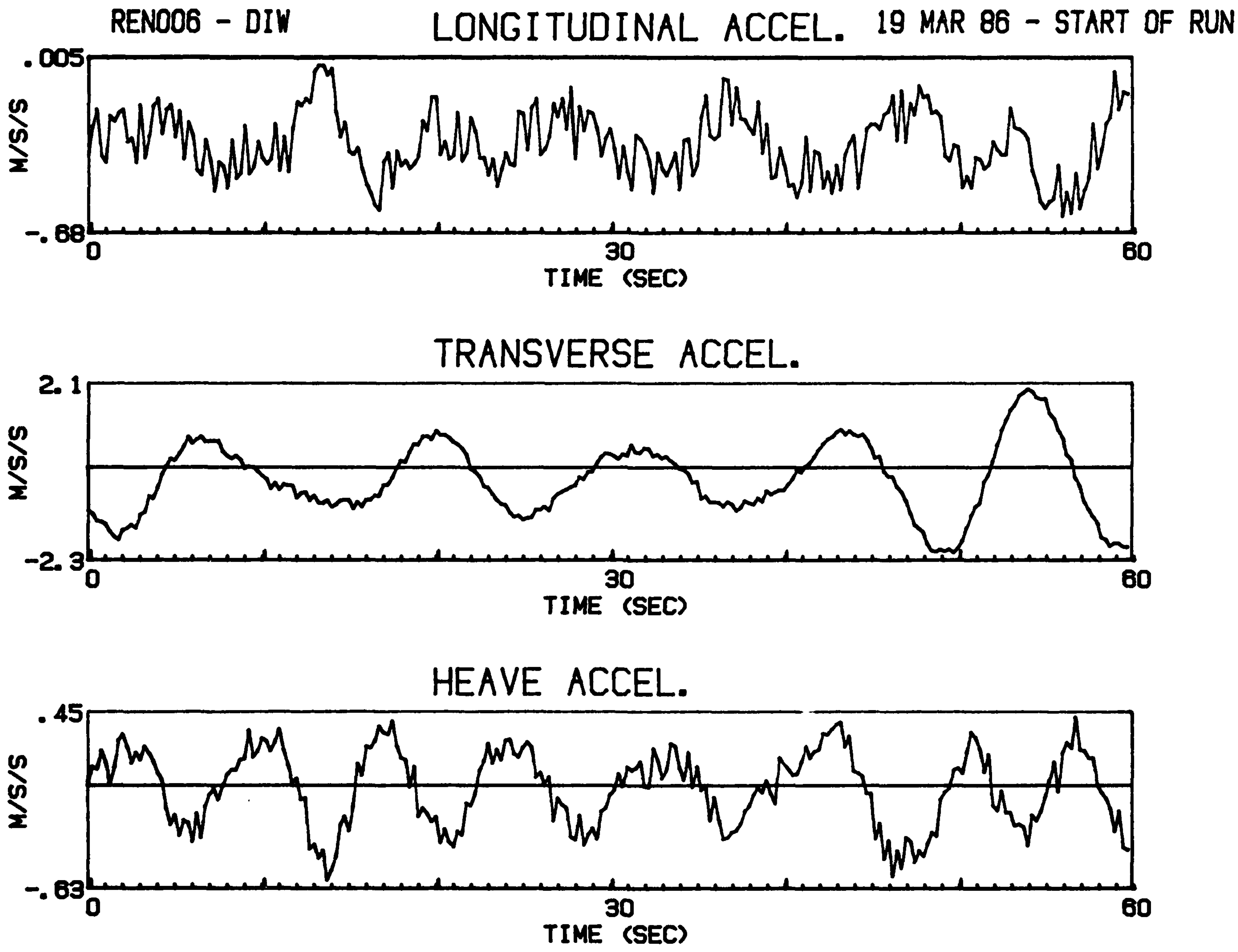


FIGURE A-3 One-Minute Segment at End of RENO6 Test

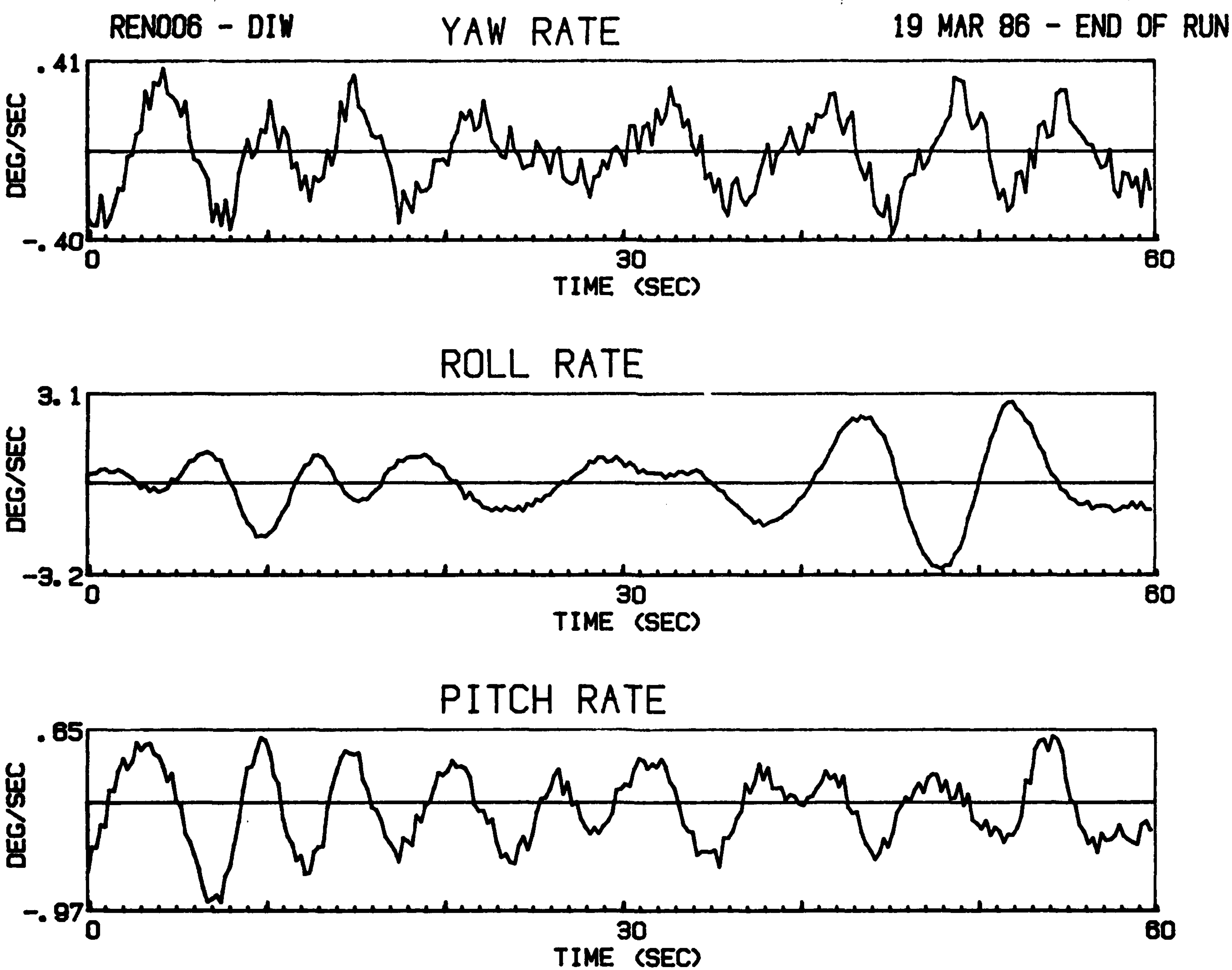


FIGURE A-4 One-Minute Segment at End of RENO6 Test

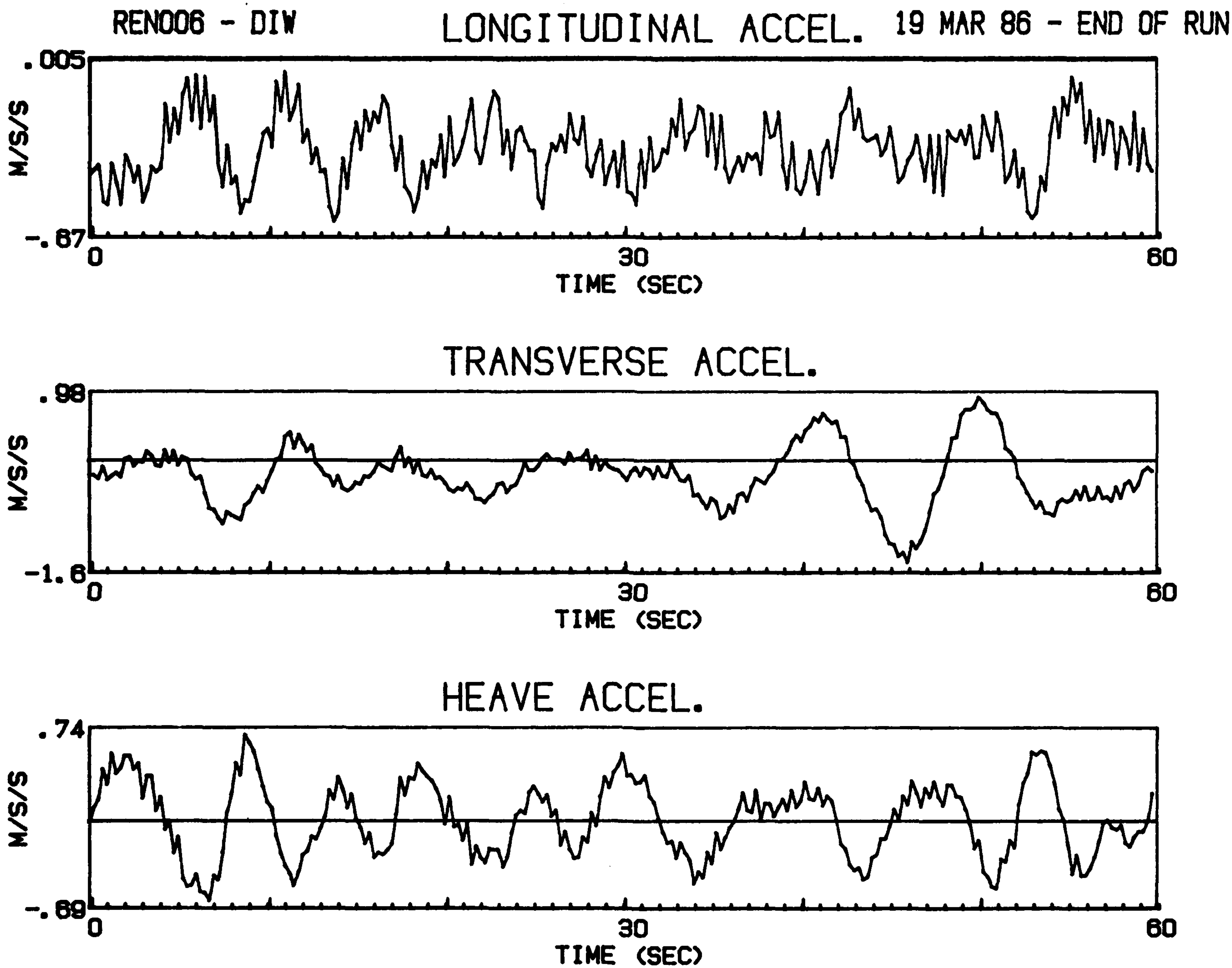


FIGURE A-5 Snapshot of Entire REN06 Segment-Roll Rate

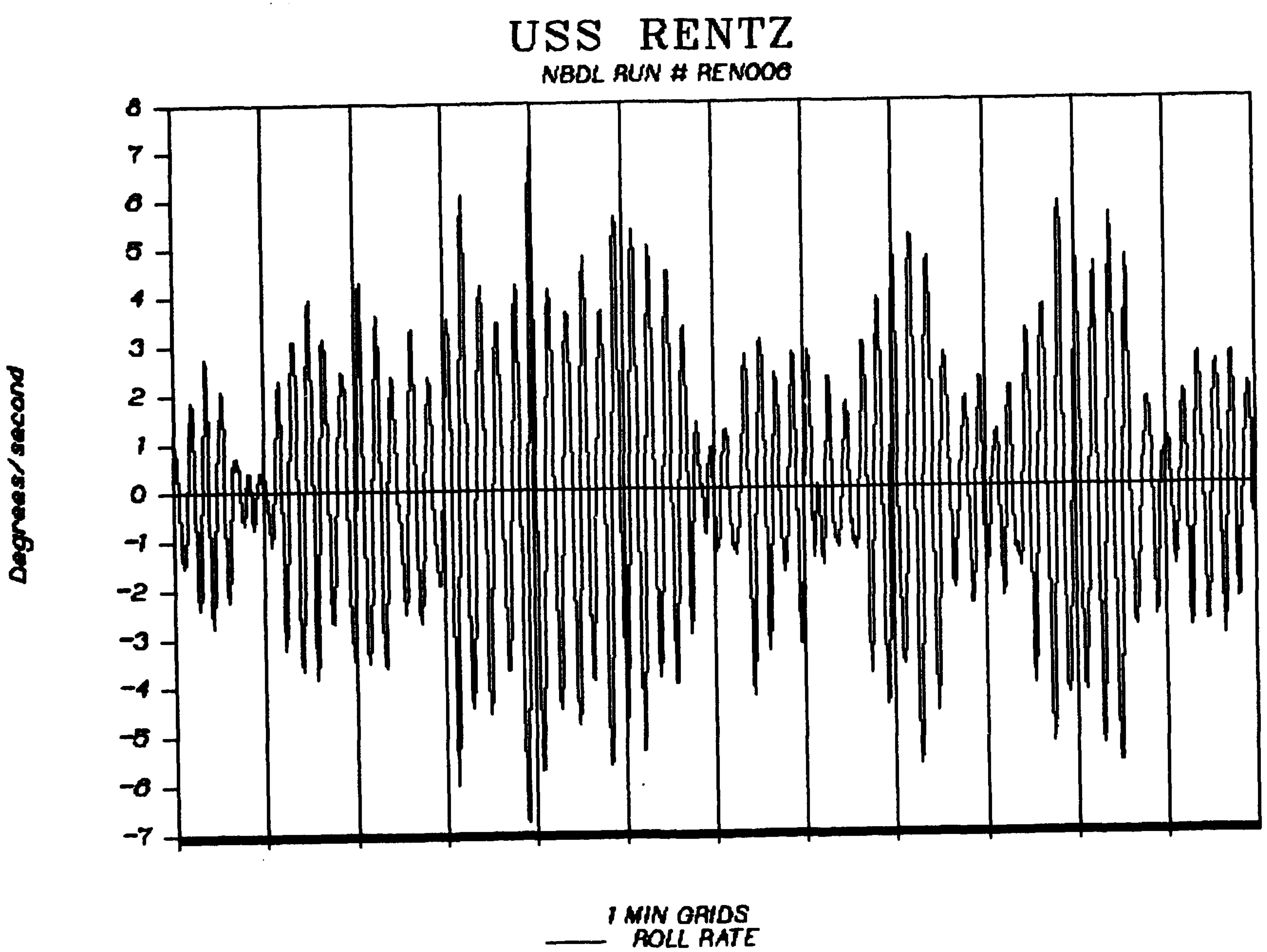


FIGURE A-6 Snapshot of Entire REN06 Segment-Pitch Rate

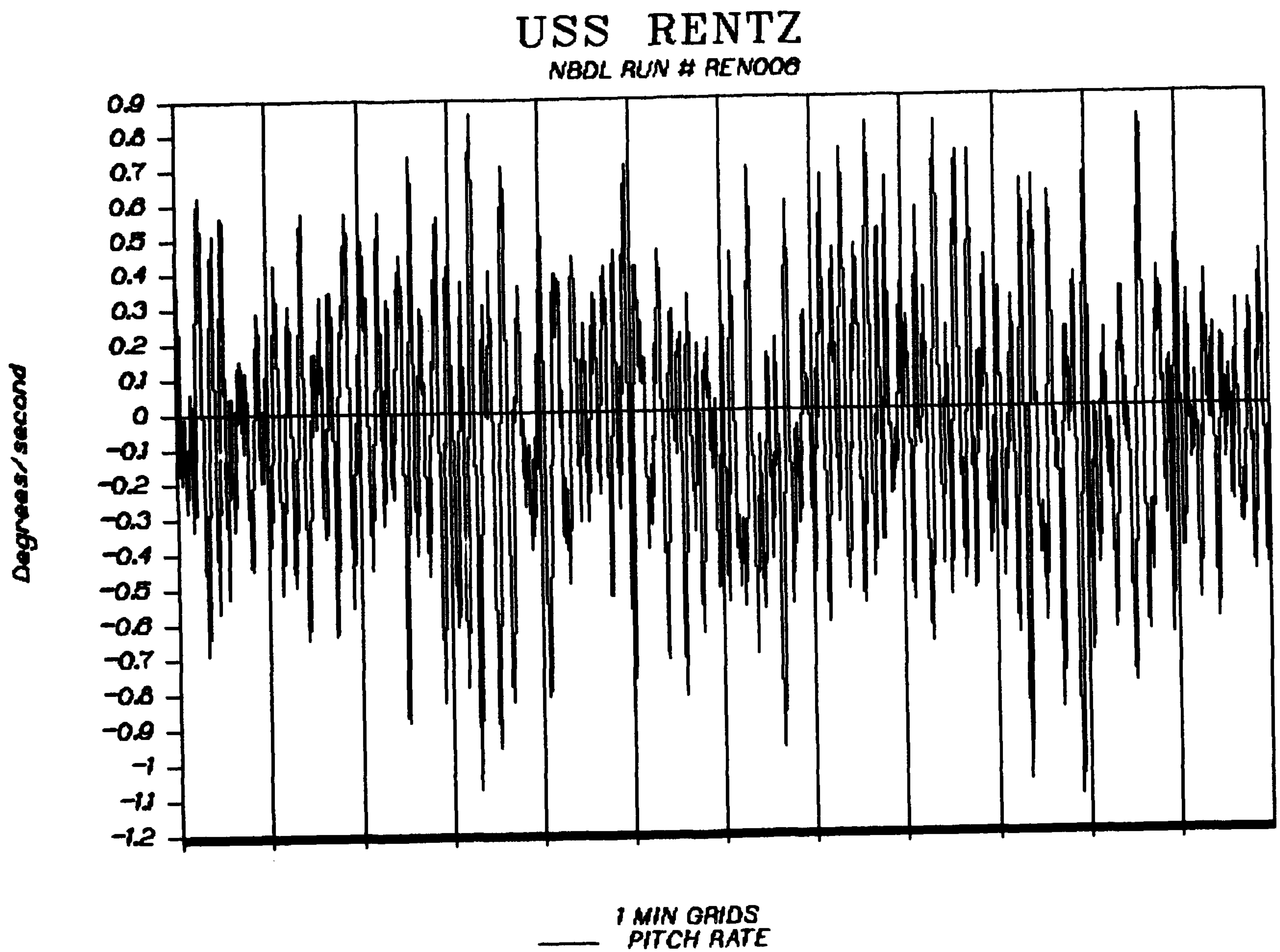


FIGURE A-7 Snapshot of Entire RENO6 Segment-Heave Accel.

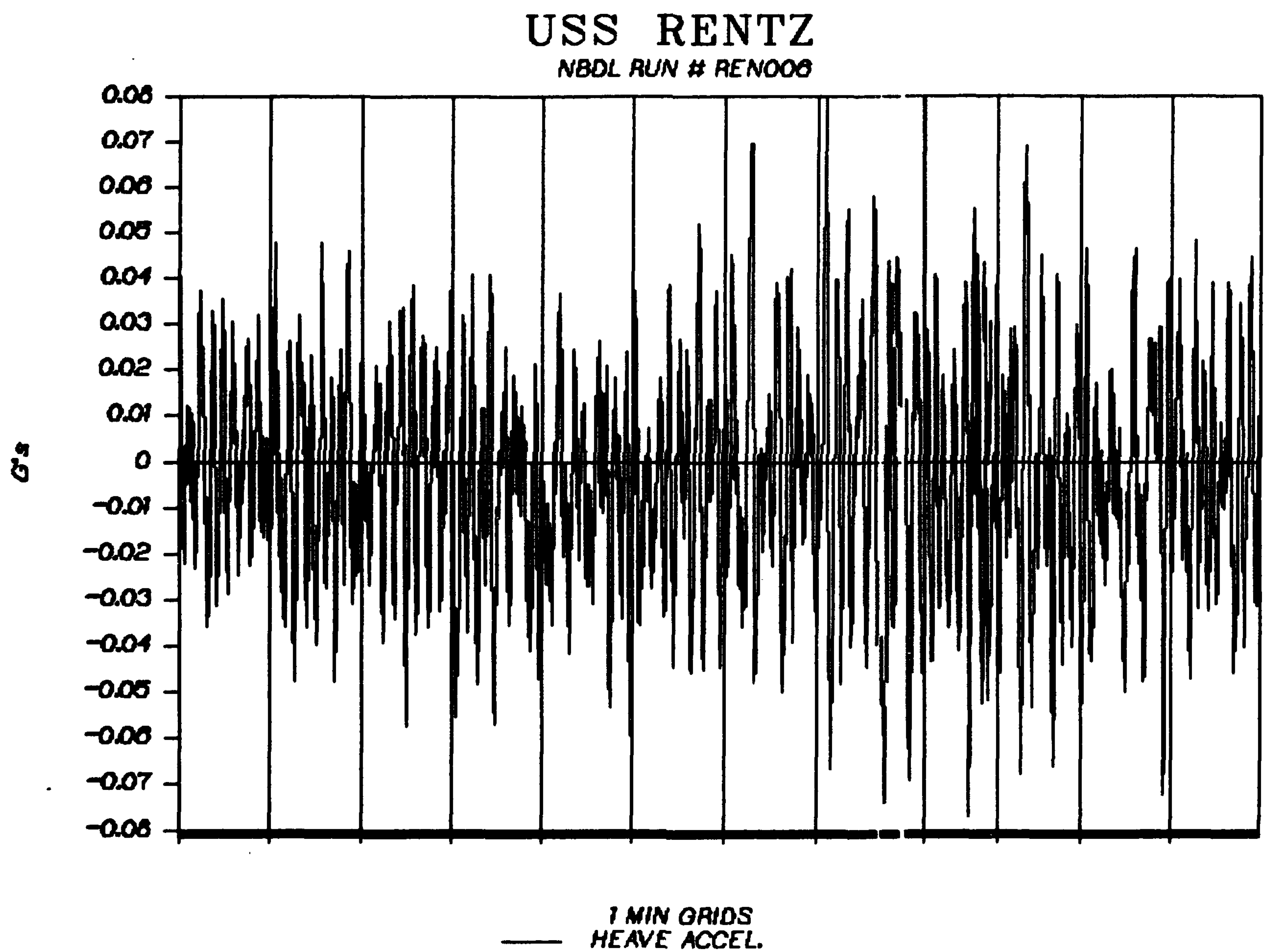


TABLE A-II

SUMMARY OF RUN: REN010

DATE..................04-01-1986
START TIME...........09:15:00
END TIME.............10:15:00
SAMPLE RATE (S/S/C).. 4
A/D SYSTEM GAIN...... 8
FIRST CHANNEL........ 0
LAST CHANNEL......... 5
OF RECS WRITTEN.... 3998

CHANNEL ASSIGNMENTS	SHIP & WEATHER INFO.
1. Pitch rate	Ship's heading: 180 deg.
2. Roll rate	Ship's speed: 22k.
3. Yaw rate	Wind direction: 30 - 40 deg.
4. Heave Accel.	Wind speed: 15k.
5. Longitudinal Accel.	Wave direction: 135 deg.
6. Transverse Accel.	Wave height: 6 - 10 ft.

Off the coast of Northern California. Though this is a moderate SS4, the combination of wave direction and roll stabilizers create a motion that is not uncomfortable.

FIGURE A-8 One-Minute Segment at Start of RENO10 Test

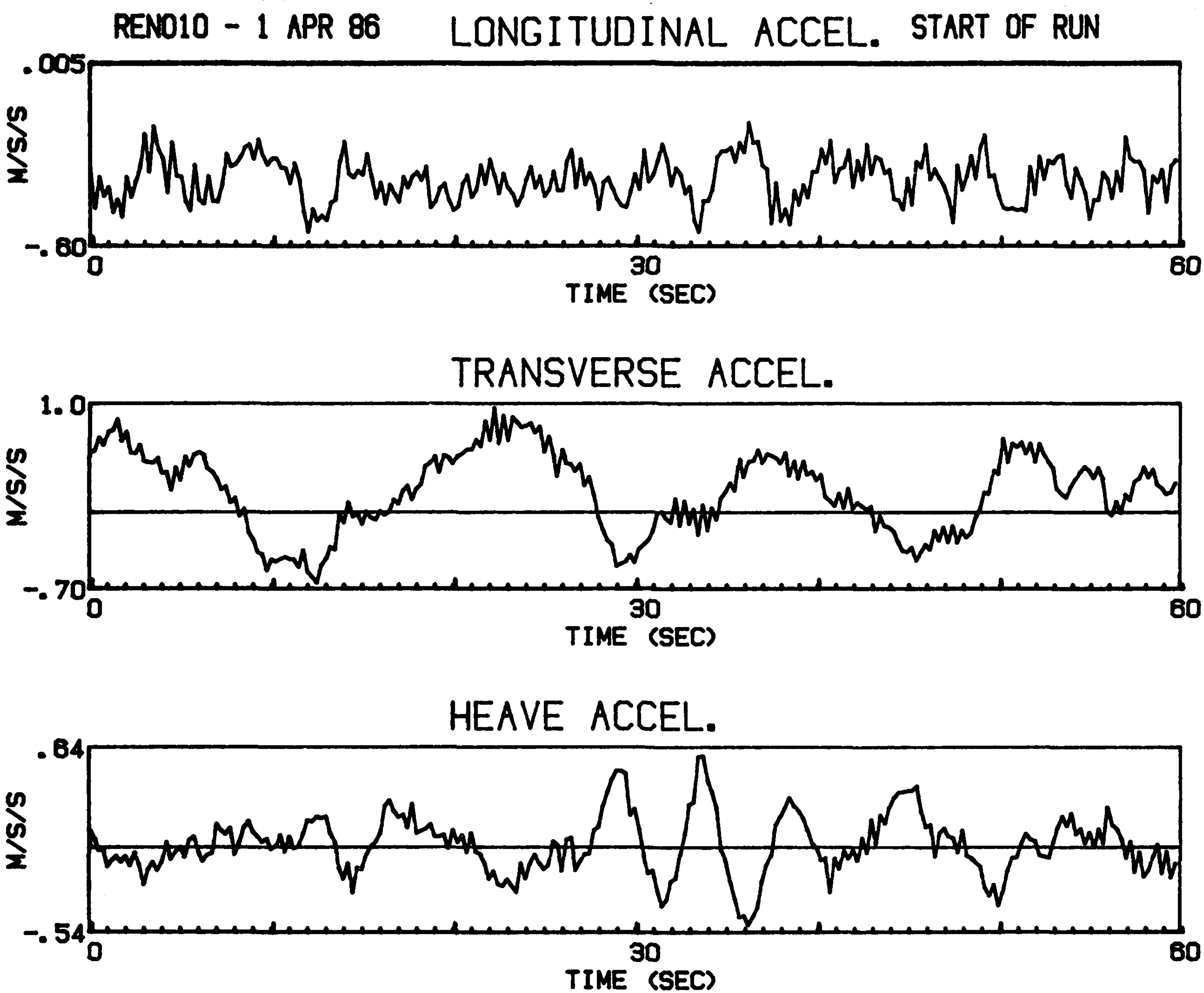


FIGURE A-9 One-Minute Segment at Start of RENO10 Test

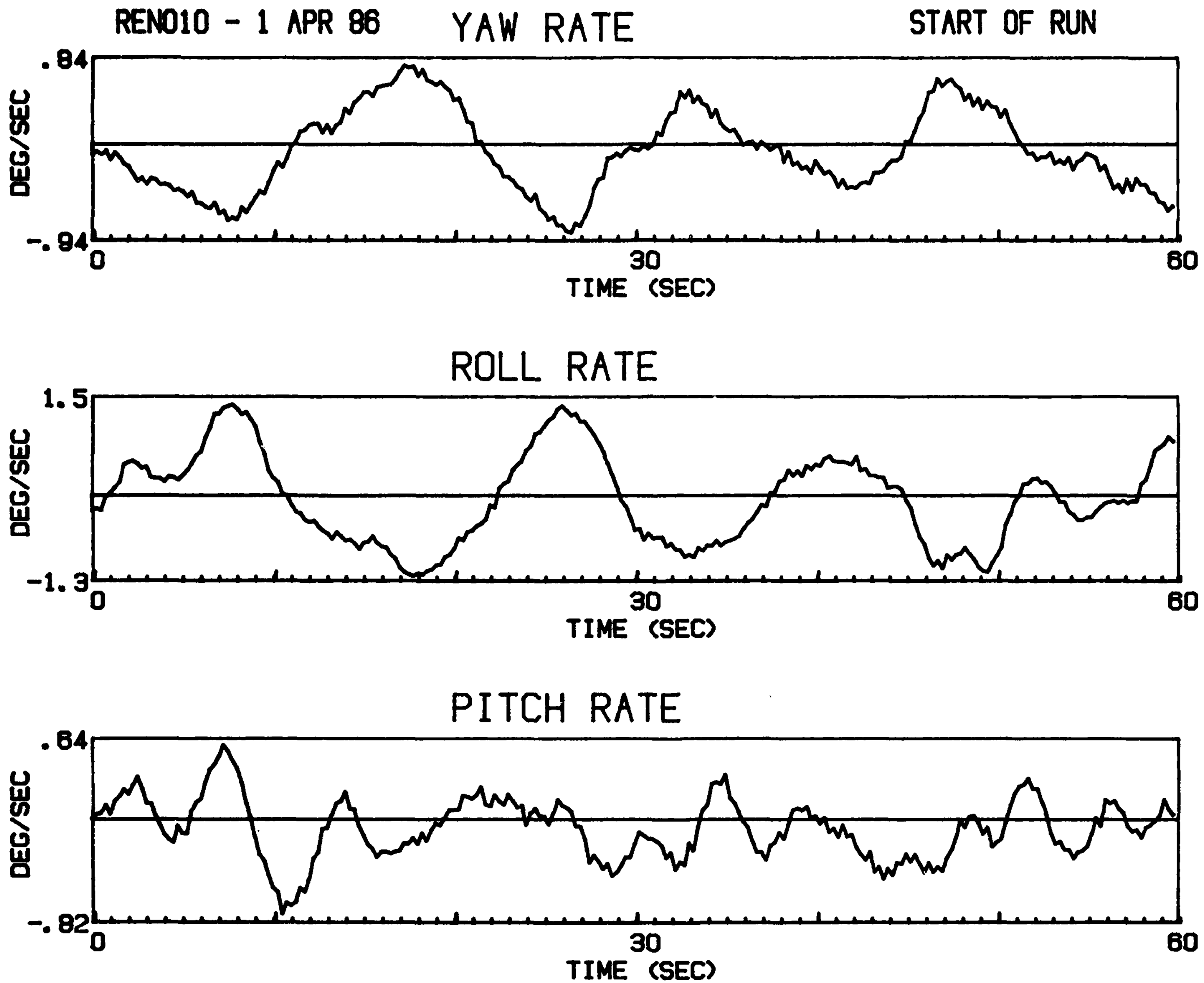


FIGURE A-10 One-Minute Segment at End of RENO10 Test

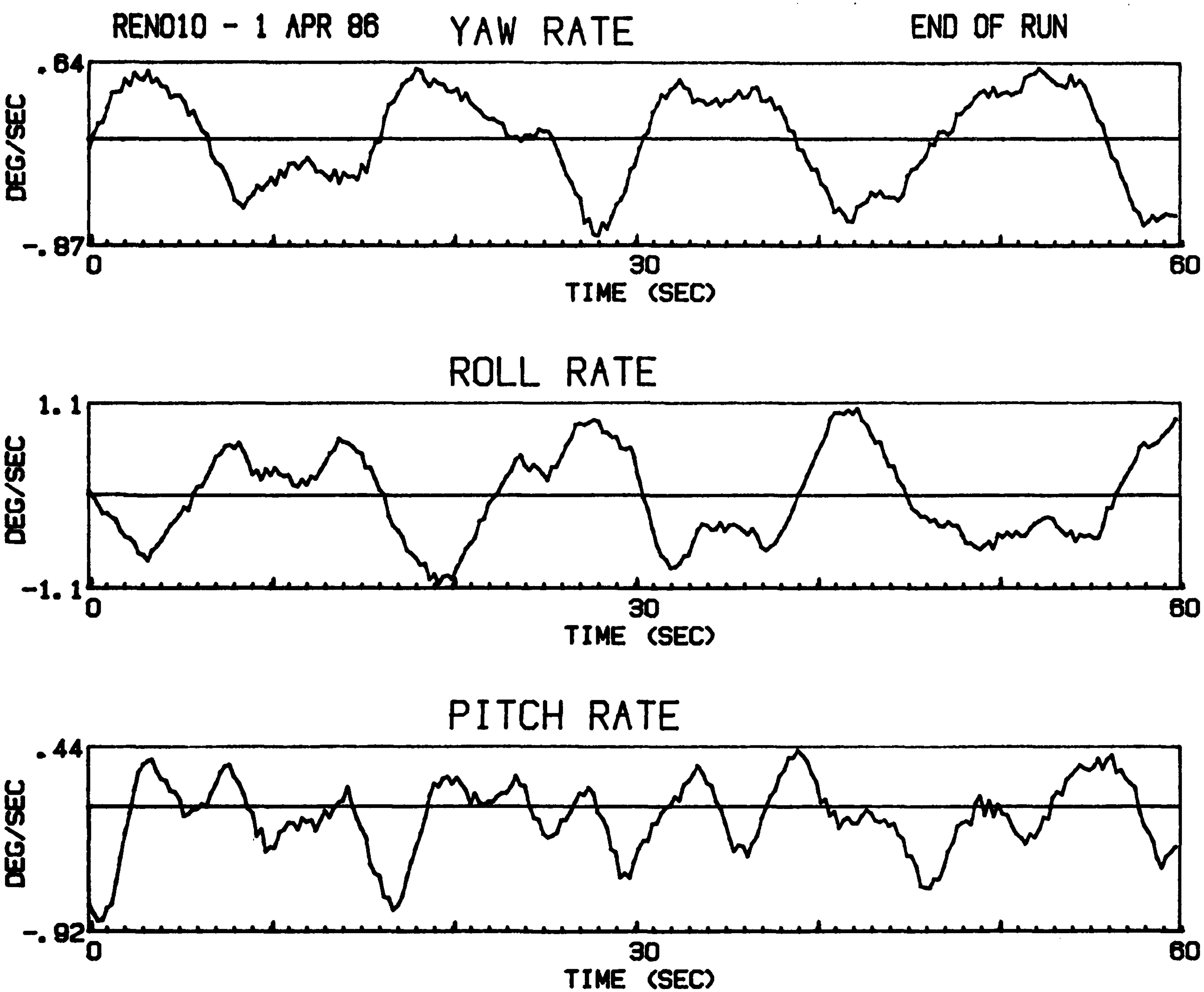


FIGURE A-11 One-Minute Segment at End of RENO10 Test

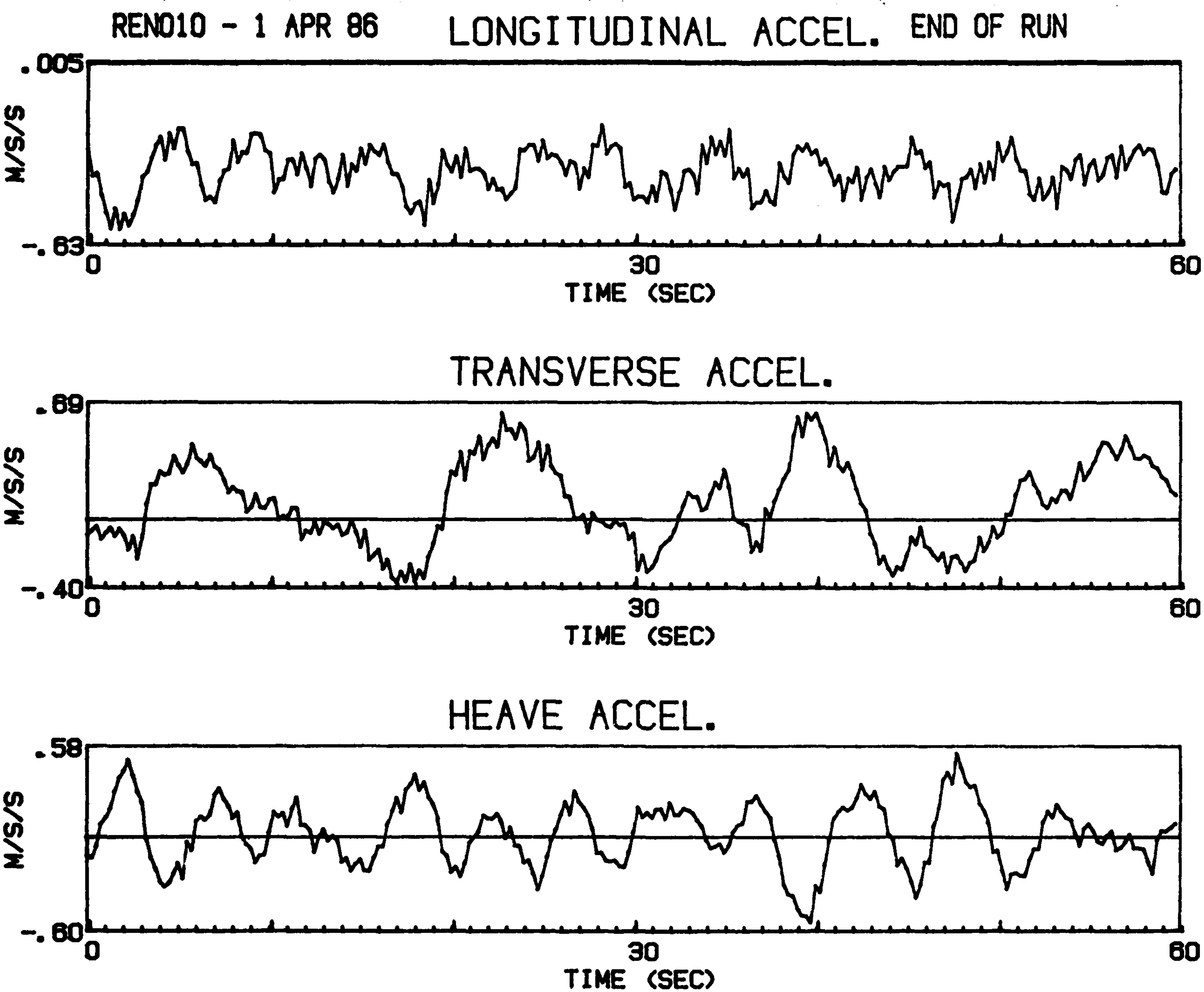


FIGURE A-12 Snapshot of Entire REN010 Segment-Roll Rate

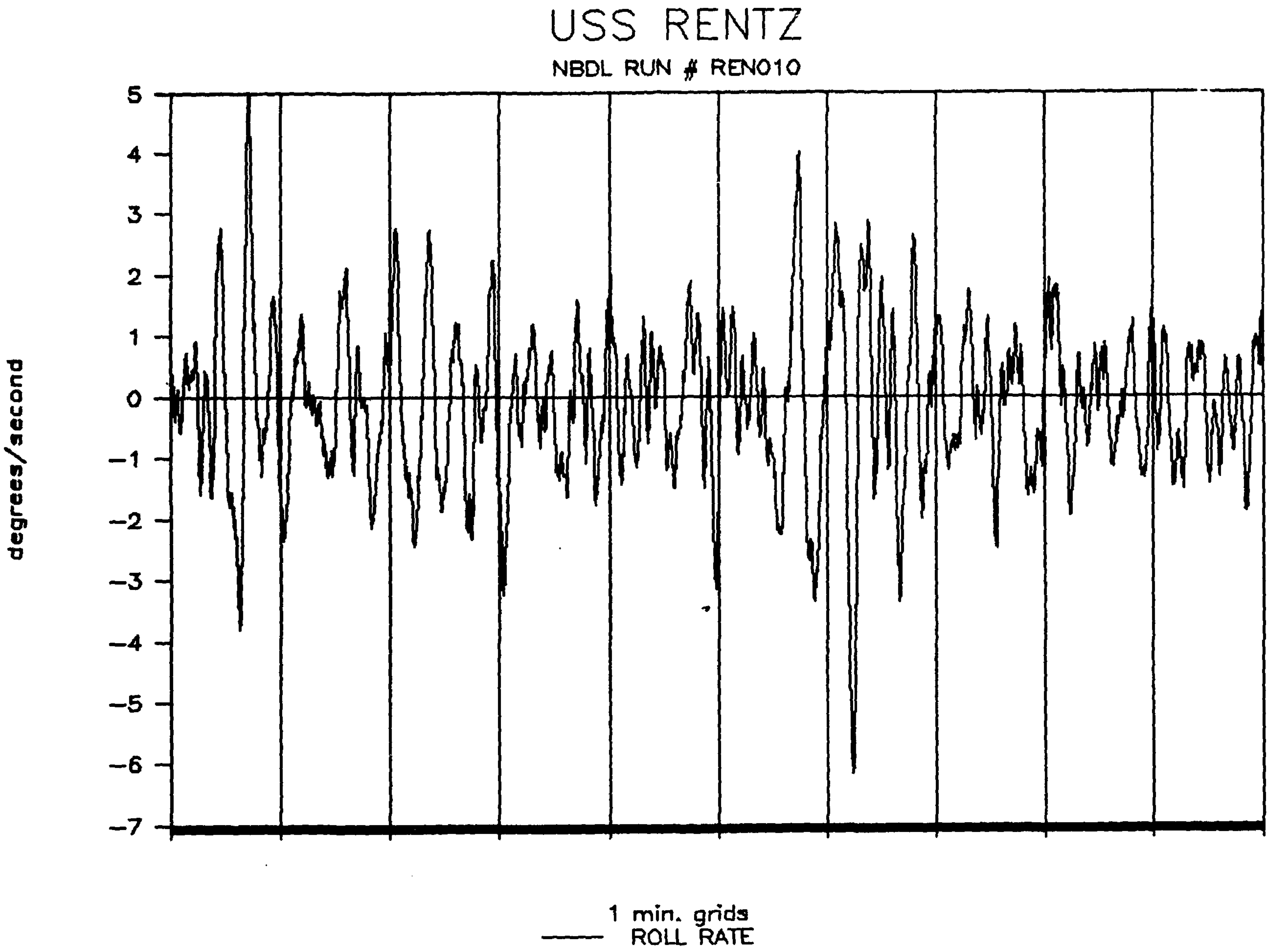


FIGURE A-13 Snapshot of Entire REN010 Segment-Pitch Rate

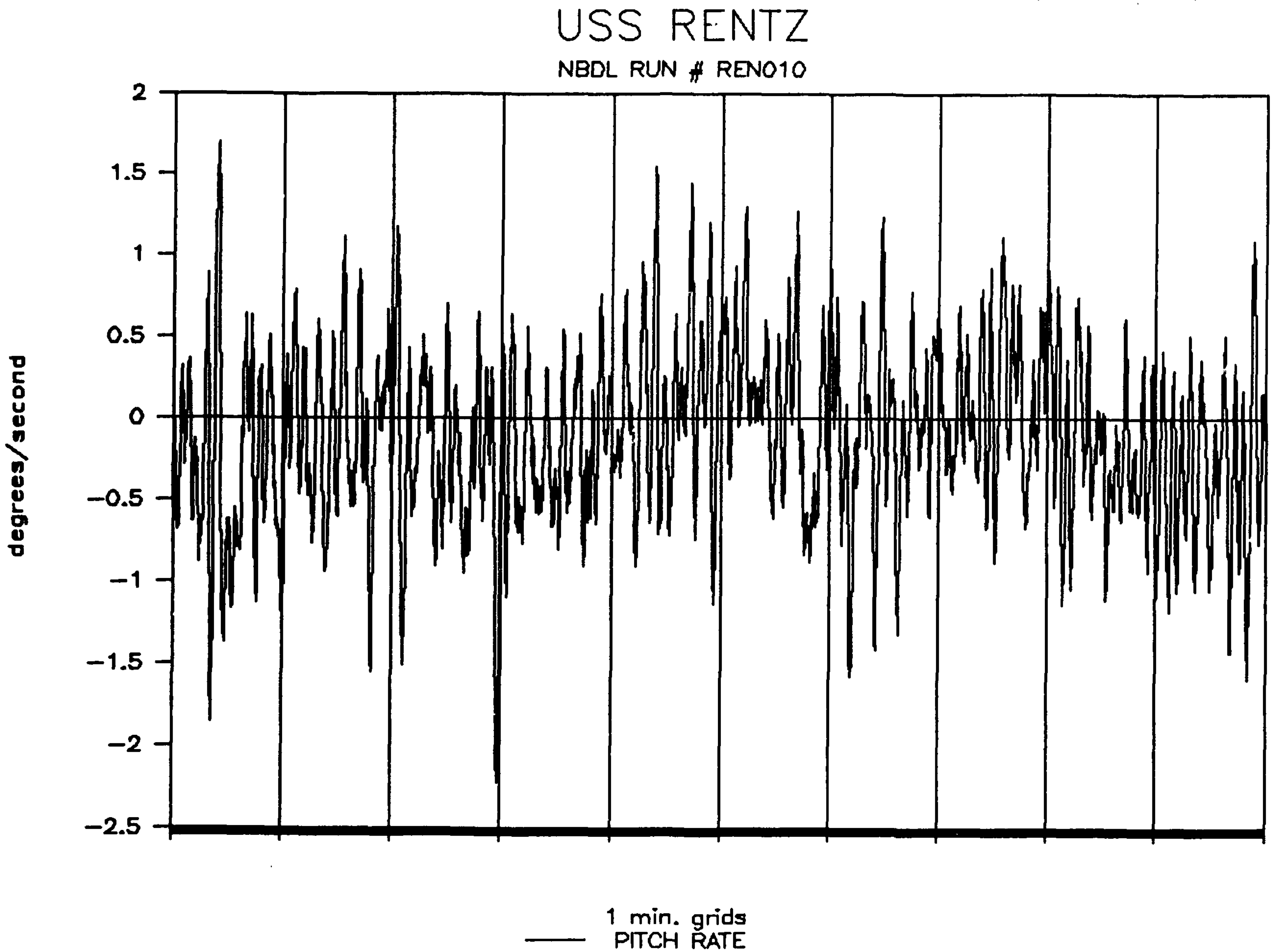


FIGURE A-14 Snapshot of Entire REN010 Segment-Heave Accel.